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PHYSICO-CHEMICAL STUDIES ON SILICA OF
SMALL PARTICLE SIZE

by

WILLIAM GLEN, B.Sc., A.R.T.C.

A thesis submitted to the University of Glasgow in fulfilment
of the requirements for the Ph.D. degree in Science.

OCTOBER, 1954.

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ACKNOWLEDGEMENTS

The author records his grateful appreciation to Professor P.D. Ritchie and Dr. Wm. Gibb for their advice and encouragement during the course of the work and for providing the necessary laboratory facilities.

Thanks are also due to Professor G. Hibberd of the Mining Department of the Royal Technical College and Dr. E.A.C. Chamberlain and Dr. Stern of the N.C.B. for helpful discussion.

The work was part of a pneumoconiosis research programme supported financially by the National Coal Board (Scottish Division).

Further thanks are due to Mr. G. Hunter for the results quoted in Table No. 6 and to Mr. A. Clunie and Staff (Tech. Chem. Dept., (Workshops)) for help in preparing various pieces of apparatus.

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SUMMARY.

Aim of Research. (i) To develop and evaluate an apparatus for the investigation of the air-settling characteristics of silica dust of a particle-size dangerous to health; (ii) to examine its use for the investigation of the effect of aqueous sprays on the dust in suspension in the chamber.

1. A brief account is given of the causation of silicosis, and the methods employed in mines to measure dust concentrations, and to suppress the fine dust particles, are mentioned.

2. The apparatus used for the preparation of a dust cloud of very fine dust particles of approximately reproducible size distribution and concentration is described.

3. An apparatus is described for the examination of the air-settling characteristics of fine silica, consisting of a dust chamber into which the dust is injected and dispersed, incorporating three pairs of compensated photoelectric cells connected in opposition and to a mirror galvanometer. A beam of light traverses the dust cloud and is picked up by one cell of each pair; the other cell picks up the beam uninterrupted by dust. The presence of dust in the chamber produces a differential current which is measured by the galvanometer.

4. A thermal precipitator (T.P.) is built into the apparatus to enable samples of the dust to be withdrawn from different depths in the chamber. The concentration (particles per cubic centimeter (p.p.c.c.)) and size distribution of each sample is estimated.

5. Two types of water spray (i) the hydraulic or water pressure; (ii) the compressed-air-operated are developed and calibrated, but only the former is used in the dust chamber.

6. Using the above apparatus the following conclusions are drawn.

A. - The atomisation of the water-pressure spray increases when (i) the pressure of the water increases; (ii) the orifice diameter increases over the range investigated; and (iii) a surface active (S/A) agent is added to the spray solution. (This effect is

more pronounced at lower pressures. All the S/A agents investigated, with the exception of Fixanol C, are found to be equally effective in increasing the atomisation.)

The compressed-air-operated spray produces smaller droplets than the water pressure spray, but is not suitable for use in the chamber because of the large volume of air involved in the atomisation process.

B. - The light extinction method was used to estimate the dust concentration and the following results obtained:-

(i) The rate of sedimentation is less at the lowest concentration of dust than at the three higher concentrations, suggesting the effect of aggregation at the latter.

(ii) The same efficiency of dust removal calculated as reduction in surface area, is achieved by spraying downwards or upwards through the dust.

(iii) The plot of reduction of dust concentration against duration of spraying does not conform to an exponential curve, as would be expected if the only factor influencing the removal of the dust was the concentration. It is suggested that the larger particles are preferentially removed by spraying, resulting in a proportionally larger decrease in surface area.

(iv) The inclusion of S/A agents in the spray solution does not result in an improvement in spray efficiency when the water pressure spray was used at a pressure of 62 lb./in.² A 0.5% solution of Lissapol NDB is as effective as water alone in suppressing the dust while a 0.5% solution of Alcopol O in alcohol is less effective than water or Lissapol NDB solution. The same efficiency of dust removal is found for a wide range of concentration of Lissapol NDB. The reason for the lower efficiency of Alcopol O solution is thought to be the increase in rate of evaporation of the spray droplets due to the alcohol in the spray solution.

C. - Application of Smoluchowski's law to the rate of decrease of concentration (p.p.c.c.) with time permits the calculation of K (the Smoluchowski constant). MSC and LAS are found to have different

values of K, both greater than the theoretical. The reasons are thought to be:-

- (i) the non-uniform size-distribution of the dust cloud; and
- (ii) the electrostatic charges which exist on the particles and which have been shown to influence the aggregation (Section 5).

The difference in the values of K found for clouds formed from MSC and LAS dusts has been attributed to the difference in the proportion of the very small particles (<1 micron) which will coagulate more quickly because of their greater mobility.

D. - Spraying tests on the dust cloud, when the T.P. was used to estimate concentration, showed that the fine silica dust cloud is affected by spraying and some of the dust removed from suspension. The amount of dust removed is increased when:-

- (i) the duration of spraying is increased;
 - (ii) the degree of atomisation is increased;
 - (iii) the velocity of the spray droplets is increased;
 - (iv) the average droplet size of the spray is decreased;
- and (v) a S/A agent is included in the spray solution at low water pressure.

E. - Estimation of the size distribution of the dust cloud under different conditions led to the following conclusions.

- (i) The size distribution of a fine dust cloud alters during the first hour in suspension, but no change in the size of the dust is detected during the next 11 hours. After 19 hours the sedimentation of the larger particles and aggregates results in a dust cloud with the same size distribution as the original dust.

- (ii) Spraying removes and breaks up the larger particles and aggregates, giving a dust cloud with a higher percentage of harmful dust particles.

- (iii) A 5% sodium chloride solution, sprayed into the chamber, results in a slight increase in the aggregation of the dust particles. This effect is not detected when a 1% sodium chloride solution is used.

- (iv) Exposure of a newly formed dust cloud to a Radioactive Static Eliminator (R.A.S.E.) resulted in immediate aggregation of the cloud to a size distribution comparable with that of a cloud which has been left to sediment for one hour. No further change in size distri-

3a.

bution is detected over the next $8\frac{1}{2}$ hours with continual exposure to the R.A.S.E.

INTRODUCTION

Mechanism and Causes of the Pneumoconioses.

Silicosis is a disease which results from the inhalation of silicious dusts, and the pathological manifestations depend on several factors, e.g. the degree of concentration of the dust in the atmosphere and the period of exposure to the dust. Silicosis increases susceptibility to tubercular infection in the victim and when infection of this type sets in the disease is rapidly fatal. Pneumoconiosis is mainly developed by miners and is caused by the inhalation of coal and rock dust and is considered by many authorities to be a modified silicosis (1).

The lung is protected from the accumulation of foreign particles by certain mechanisms. The nose through which the respiratory tract opens to the surface of the body is guarded by a coarse filter of hairs. Behind this is a series of tortuous passages with moist walls which trap many smaller particles. In addition the nasal cavities and the remaining portions of the upper respiratory tract, the pharynx, the trachea and the bronchi are lined by cells covered by minute vibratory hairs and cilia. Wavelike vibrations of these hairs tend to carry particles lodging on the surface away from the lungs and back towards the surface of the body. Particles that succeed in passing these barriers and penetrate to the terminal air spaces of the lungs are ingested by wandering scavenger cells or phagocytes, which come from the

partitions between the air spaces for this purpose. These cells move independently and tend to carry the foreign particles out of the air spaces into a special drainage system known as the lymphatics. For ordinary atmospheric pollution these protective mechanisms are adequate to prevent significant accumulation of foreign particles in the functional part of the lungs. If a person continues to breath a very dusty atmosphere for long periods of time the protective devices cannot cope with the situation, the mechanisms are damaged and the dust particles collect where air should be (2).

According to Kasten (3) coal dust is phagocytised more quickly and more completely than stone dust. Quartz causes violent changes, the smaller the particles the more quickly the process develops, and Kasten concluded that the malignity of quartz is caused by its physicochemical effect on the tissues (surface effect).

At present there is a lack of knowledge as to the size of airborne dust likely to be harmful. Present day standards of air dustiness are based on numerous uncertain premises. Different authorities found, in the lungs of diseased silicotics, varying maximum and minimum sizes of dust ranging from as small as 0.2 micron to as large as 10 microns (4, 5).

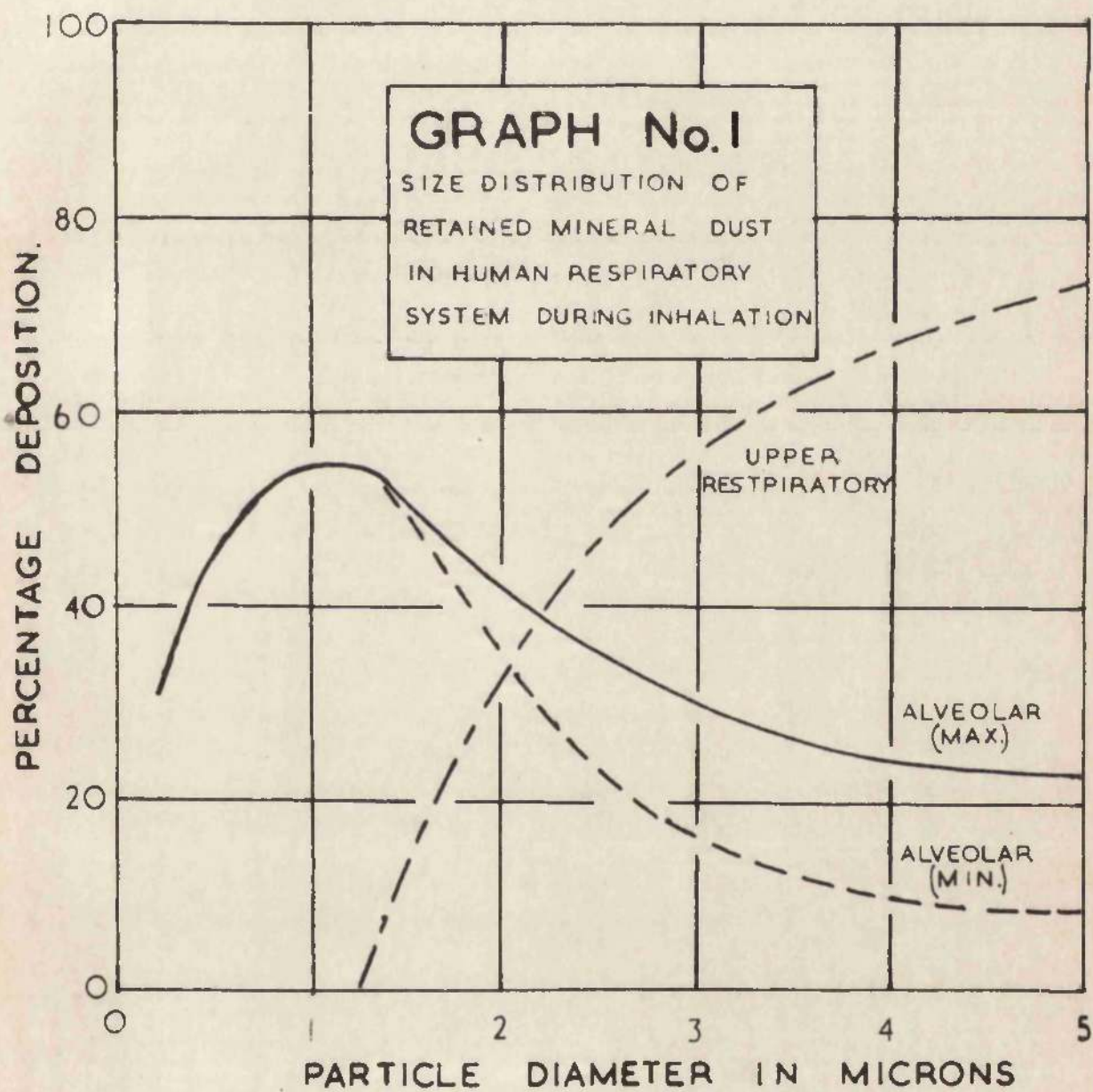
(1 micron = 10^{-4} cms = 1/25,400 in. This has led to the conclusion that the particle size of dusts which are harmful to the lungs lies between a lower limit of 0.2-5 microns and an upper of 6 - 10 microns. The reason for the exclusion of <0.2 micron from the dangerous

fraction was that optical microscopes had been used in the size analysis and <0.2 micron particles were not detected.

More recent work by Hatch (6) has indicated the relationship between the amount of dust deposited in the lungs during inhalation (the dosage rate) and the amount in the air. This relationship is determined by the behaviour of particulate matter in the respiratory system. It has long been known that only a fraction of inhaled dust is retained and that the percentage retention varies with particle size.

Physical and mathematical considerations indicate that the depth of penetration of inhaled particles into the respiratory system will increase with decreasing particle size. On the other hand, according to the same laws, the percentage deposition of particles reaching any given depth of penetration decreases directly with size. Thus there are two opposing factors at work in the respiratory tract, from which it follows that there must be a particle of a certain "optimum" size having the greatest probability of penetrating to and being retained in the alveoli. Larger particles will be relatively scarce in the alveoli because of earlier deposition in the upper respiratory tract, and finer particles will decrease in number because of lower retention. Such a relationship has been predicted mathematically and derived indirectly from measurement of total retention. It has also been confirmed in human lungs by two different techniques (4, 7).

Graph No.1 (6) represents the distribution of retained mineral dust in human respiratory system during inhalation in relation to particle



size. Note the maximum alveolar retention at one micron.

It would seem poor reasoning to hold that the only harmful sizes are those found in the lungs, because dust particles, ranging from 10 to 100 microns or more when floating in the air, are drawn into the nostrils and other protective air passages, and, if in large numbers, soon clog these protective agencies and passages, permitting free unobstructed entrance of the so-called harmful dusts. It appears that any dust insoluble or difficultly soluble in the fluids of the respiratory passages, and in sufficiently finely divided form to float in the air and be breathed in considerable quantities by workers over long periods, will be ultimately harmful. Although free silica (SiO_2) has been considered the most harmful, silicates (e.g. asbestos) have been found to be almost as dangerous (8,9,10).

The exact process by which fibrous tissue is formed in the lung as a result of the presence of dust is not known. At one time investigators believed that fibrosis was produced in response to the irritation caused by the hard sharp quartz particles as well as through filling or partial filling of the lungs with dust - that is, the dust was supposed to act mechanically. This theory was displaced when Gardner (11) showed that fine carborundum powder having a hardness greater than that of silica was inactive in the lungs of animals. Kettle (12), by coating silica particles with iron oxide, and Denny, Robson and Irwin (13), by using alumina as a coating, showed

that an initially pathogenic silica dust could be rendered harmless.

At present most investigators (12,14,15,16) consider solubility a primary factor in the harmfulness of silica and claim that a substance insoluble in the respiratory fluids and tissues cannot cause dust diseases of the lungs. They believe that the action is chemical rather than mechanical. A more rational view would seem to be that the harmful action is of both chemical and mechanical origin.

Dust Sampling, Measurement, and Analysis.

The airborne dust particles present in the atmosphere of a mine may be as large as 150 microns in size or so small that the particles cannot be detected even with a powerful optical microscope, i.e. <0.2 micron. The average particle of atmospheric dust found in bituminous coal mines is 0.5 micron or about 1/50,000 of an inch in maximum dimension (17).

The formation of dust depends on a number of factors. If coal is hard, it generally will produce less dust during mining and handling than coal of soft structure. Other factors include the height of the coal bed and the elevation at which the coal is cut. The speed of cutting also alters the amount of dust produced. Other things being equal, the higher the speed of the cutting chain in a machine the greater the quantity of dust formed. Dull drill-bits (17) are a productive source of fine dust because of the increased attrition of the coal.

It is impossible to define dangerous concentrations of airborne dust accurately owing to the meagre data available. It is now generally agreed (18) that men can work in relative safety in atmospheres containing not more than 850 coal (or 650 anthracite) 1 - 5 micron particles, or 450 rock 0.5 - 5 micron particles per cubic centimetre of air.

When measuring dust concentrations very large particles have a great effect on the mass concentrations, and therefore in studies on pneumoconiosis dust concentrations are commonly expressed in terms of the particle count.

The dust concentration in a mine can be measured by a number of sampling devices, the four most commonly used being:-

1. The Konimeter.
2. The Owen Jet Dust Counter.
3. The P.R.U. Hand Pump.
4. The Thermal Precipitator (T.P.).

The Konimeter and Owen Jet Dust Counter are sampling instruments of the impinger type; both impinge a measured sample of the air on a prepared surface.

In 1916 Kotze (19) called attention to an instrument which he called the konimeter. This consists of a chamber, one side of which is a vaseline-coated glass plate, and an impinging orifice which is perpendicular to the slide. The air is sucked out of the chamber by a cylinder and a spring-actuated piston. The only method of ingress of air is through the impinging orifice, and

and when the air enters the chamber at high velocity in this manner the dust is deposited in the form of a spot on the greased plate. The particles may be counted under a microscope using a ruled eyepiece.

The Owen Jet Dust Counter, developed by Hatch and Thompson, has many desirable features with respect to simplicity and rapidity in operation. The modified Counter permits the direct collection of eight samples on a single glass slide, and the "dust ribbons" are matched against a series of standard ribbons under a comparison microscope. The Konimeter and Owen Jet Dust Counter are subject to criticism since the percentage of the dust trapped on the glass slide is only a small proportion (20 to 60%) of the dust contained in the sampled air (20). It is also claimed that the impinger method forms aggregates on the slides and breaks up some particles.

With the P.R.U. hand pump, the dust-laden air is drawn through a filter on which the particles are deposited. The stained filter is then examined and the concentration estimated by the depth of the stain. When the dust cloud is composed of white particles, a black filter is used. This technique does not distinguish between a large particle of dust and a number of small particles, and is used mainly in rough comparative work.

The fourth sampling instrument, the T.P. designed by Whytlaw-Gray and developed by Green and Watson (21,22), has an efficiency of 100% for particles of dust from above 20 microns down to at

least 0.2 microns. The deposits are examined under a high-power microscope and size distribution and concentration counts carried out on the samples. From the industrial point of view the instrument gives the best indication of the dangerous nature of the dust, but it has the disadvantage that the sample has to be examined by a microscopist and is time-consuming. The instrument is best suited for work of great accuracy.

The light-extinction method for estimating dust concentration has found much support in laboratory work on sedimentation of dusts. The method is best suited for control and comparative purposes as the results obtained are difficult to interpret.

Dust Suppression in Coal Mines.

Dust suppression can be accomplished by one of two ways, either by (1) modification of the dust-generating process, i.e. preventing dust formation at its source, so that much less dust is disseminated, or (2) by subsequent removal of airborne material.

The main methods of suppression at the source which have been tried are wet cutting with and without a wetting agent, the use of foam, and water infusion (22).

When water sprays are employed to suppress dust, the spray is formed by forcing water at high pressure through a fine orifice or by atomising the water with compressed air. Both types of sprays have been investigated under mining conditions to compare

their efficiencies. Recent investigations have shown that the compressed-air-operated sprays are most effective in removing airborne dust after blasting. The effect of this type of spray in removing the dust is twofold.

(1) The water droplets in the spray remove the dust from the atmosphere by knocking the particles down.

(2) The large volume of air used to atomise the water increases the ventilation and displaces the dust from the site.

Efficiencies of 99% have been claimed for these sprays within 10 to 15 mins after blasting (23). The compressed-air-operated sprays are used with pneumatic picks and drills where the exhaust is used to atomise the water.

It has been found that for dust not already airborne effective application of water may be obtained only by the right degree of atomisation (24,25). In general a finer spray gives a better result. Relatively high pressures are necessary (60-120 lb./in.²) for fine atomisation in the water-pressure type of spray used in the mines.

The use of wetting agents for reducing the amount of water necessary to suppress dust has been investigated by nearly all interested research organisations. During coal cutting it was found that the use of solutions of wetting agents as sprays produced a greater reduction in the dust concentration than did a much larger quantity of water alone (22).

As an alternative method of suppressing dust at its source foam as used for fire fighting has been suggested. Price (26) claimed very effective dust suppression with foam, but in pits where more stringent dust conditions prevailed the results obtained were inconclusive. While the method is more complicated than the use of solutions of wetting agents as sprays, the quantity of aqueous foam solution used is very much less.

The water infusion method for the suppression of dust was developed in the anthracite area through the joint efforts of the staffs of the Amalgamated Anthracite Collieries Ltd., and of the Mines Inspectorate (27). It consists briefly of injecting water under pressure in boreholes driven in the coal face to a depth which must be determined from existing conditions but is usually between five and fifteen feet. The pressure applied also depends on mining conditions and may be between 30 and 300 lb./in.² Although applied with beneficial results it does not remove the dust completely.

While it is much better to deal with dust at its source, this is not always possible, or is only partially successful. Separation of the dust from the air must then be carried out through the agency of mechanical, electrical, or thermal forces.

Mechanical methods involve gravity settling tanks and elutriators. Under this heading come cyclones, scrubbers, etc., which depend on the inertia of the particles. These methods are very effective in removing larger particles with relatively high inertia but are not so efficient with small particles in the range responsible for

pneumoconiosis.

The dust-laden air generated by the mining processes can be purified by drawing the air away by an air draught either to a place where it can be harmlessly discharged or to a filter or separator of some kind where the particles can be removed. Mechanical methods have the greatest application, but separation by thermal diffusion is another possibility for small particle-size ranges. The electrostatic precipitator is also much used to remove airborne dust, but it has the disadvantage that it constitutes a fire hazard in mines.

Object of the Research.

Although a great deal of work has been carried out in the mines on the suppression of fine dusts by sprays and other means, a review of the literature shows that very little has been done on the suppression of airborne dusts by aqueous sprays under controlled laboratory conditions.

The object of the research was to build apparatus suitable for investigating the mechanism of sedimentation of fine airborne silica dust and determining the effect of aqueous sprays on the dust cloud. Apparatus was built to generate a dust cloud of approximately reproducible concentration and size distribution. A spray unit was used to investigate the influence of different variables (e.g. orifice of the spray nozzle and surface tension of solution) on the size distribution of the spray produced. After calibration of the spray unit, sprays with different characteristics could be

injected into the chamber and their effect on the efficiency of the dust cloud examined.

The concentration of the dust cloud in the chamber was measured by:-

- (1) the light extinction method;
- (2) the thermal precipitator.

The first gave a measure of the surface area of the dust cloud in suspension, while the thermal precipitator enabled both the concentration in particles per cubic centimetre and the size distribution to be found. The light extinction method was used in the initial experiments, but owing to the lack of information on the size distribution of the particles in the dust cloud the results obtained by this method and the limited range of concentration, the thermal precipitator was used in subsequent experiments to show how the concentration and size distribution altered during sedimentation and spraying, and also to enable tests to be carried out over a wide range of dust concentration.

SECTION 1Investigation of Water Sprays.

The mechanism of atomisation, or disintegration of liquid jets, has been investigated by many workers in an attempt to obtain a relationship between the variables of an injection system and spray performance.

The performance of the spray depends upon:-

- (1) the cone angle of the spray;
- (2) the average droplet size;
- (3) the droplet size distribution;
- (4) the throughput.

Liquid jet disintegration at low velocity is fairly well understood, but the process of sudden atomisation at high discharge velocities such as exist in an actual injection system has not as yet been clearly explained nor quantitatively analysed.

The disruption of a liquid jet discharged from the orifice of an atomiser with a certain velocity has been shown to be affected by three factors, viz. (i) the initial disturbance of the liquid flow in the atomiser, which affects the turbulence in the jet, (ii) the properties of the medium into which the jet is discharged, and (iii) the physical properties of the discharged liquids. Each of these factors contributes to a certain extent to the process of spray formation but the part played by each in the disruption of the jet is as yet unknown.

A change in the physical properties of the liquid is known

not only to have an effect on the process of droplet formation, and thus on droplet size, but also to influence the spray indirectly by an additional effect on the type of flow, whether laminar or turbulent, through an atomiser. Owing to the difficulty of separating these factors no definite conclusion has been reached on their relative importance in the process of spray formation.

Rayleigh (28) offered one of the first theories of the disruption of a liquid jet when he made a mathematical analysis of the stability of a non-viscous jet and derived the condition for the disruption of the jet. The general conclusions of Rayleigh's work were accepted in later theories by Haelein (29), Weber (30) and Castleman(31).

In an analysis of spray formation Schweitzer (32) stressed the importance of turbulent flow in the atomiser. This view of primary disturbances and turbulent flow was shared also by Mehlig(33) and Oschatz (34). Mehlig attributed the spray formation to the radial components of liquid velocity existing in a turbulent flow, while Thiemann attributed the disruption of the jet to increased relative velocity between the outer liquid layer and the air owing to turbulence.

Holfelder (35) and Haenlein (29) observed, by means of high speed photography, the disruption of a liquid jet as the discharge velocity increased. The results of these experiments have been confirmed theoretically by Weber's calculations for the initial stages of jet break up. Nukyama and Tanasawa (36), by their

photographic studies of spray formation, distinguished three types of jet disintegration as the velocity of discharge increased.

In general the action of the liquid viscosity and surface tension oppose the disintegration of a liquid jet. High viscosity decreases the rate of breaking up of distortions of the droplets formed initially and increases the final droplet size. According to Hinze (37) the action of surface tension is twofold. In the initial stages of the development of surface distortions into ligaments, and of the deformation of the droplets, surface tension opposes the process, but assists in the final stages of disruption. Since, however, the development of the initial stages of formation of the distortions is important for atomisation to proceed, an increase in the liquid surface tension will cause a decrease in the efficiency of atomisation. The importance of surface tension in the mechanism of atomisation has also been stressed by Klusener (38) and Littage (39).

Since insufficient information was available to enable us to estimate the changes in spray characteristics produced by varying conditions of orifice size, surface tension etc., it was necessary, in order to understand the effect of different sprays on the efficiency of suppression of airborne silica dust, to investigate the behaviour of the sprays when certain characteristics of the spray nozzles and liquid were altered.

Two types of water sprays were investigated:-

- (1) the liquid pressure or hydraulic spray;
- (2) the compressed-air-operated spray.

Experimental.

The two types of spray investigated were attached to apparatus which enabled the pressure of the liquid in one case, and the quantity of air and water in the other, to be controlled and measured.

Liquid Pressure Spray.

The nozzles for the liquid pressure sprays (Fig. 1) were the same as those used in commercial insecticide sprayers and consist of two parts, one screwing into the other. The water is forced under pressure along a helical groove in the inner part and out through an orifice in the outer chamber.

Orifices of different diameters were drilled in the nozzles so that their influence on the spray produced could be investigated. Four of the nozzle chambers were drilled to different diameters, but in three of these (Nos. 2-4) the same helical groove was used. The nozzle diameters are shown in Table 1. The apparatus used with the liquid pressure nozzle is shown in Fig 1 and consists of a hand-operated commercial plunger-type pump fitted to a pressure vessel. The output from the vessel passes along a length of pressure tubing to the spray nozzle. A screw clip on the tubing enables the spray to be turned on and off as desired. The pressure tubing is connected by a T-piece to a pressure gauge which shows when the vessel has been pumped up to the required pressure. The pressure is maintained at this value by occasional manipulation of the plunger.

It was found convenient to use water in the pressure range

WATER PRESSURE SPRAY NOZZLE

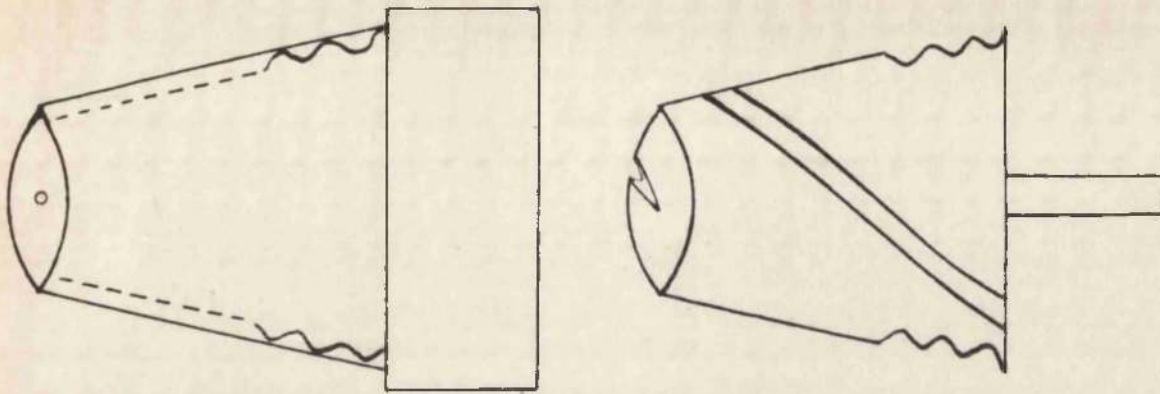


FIG. No. I

SPRAY UNIT

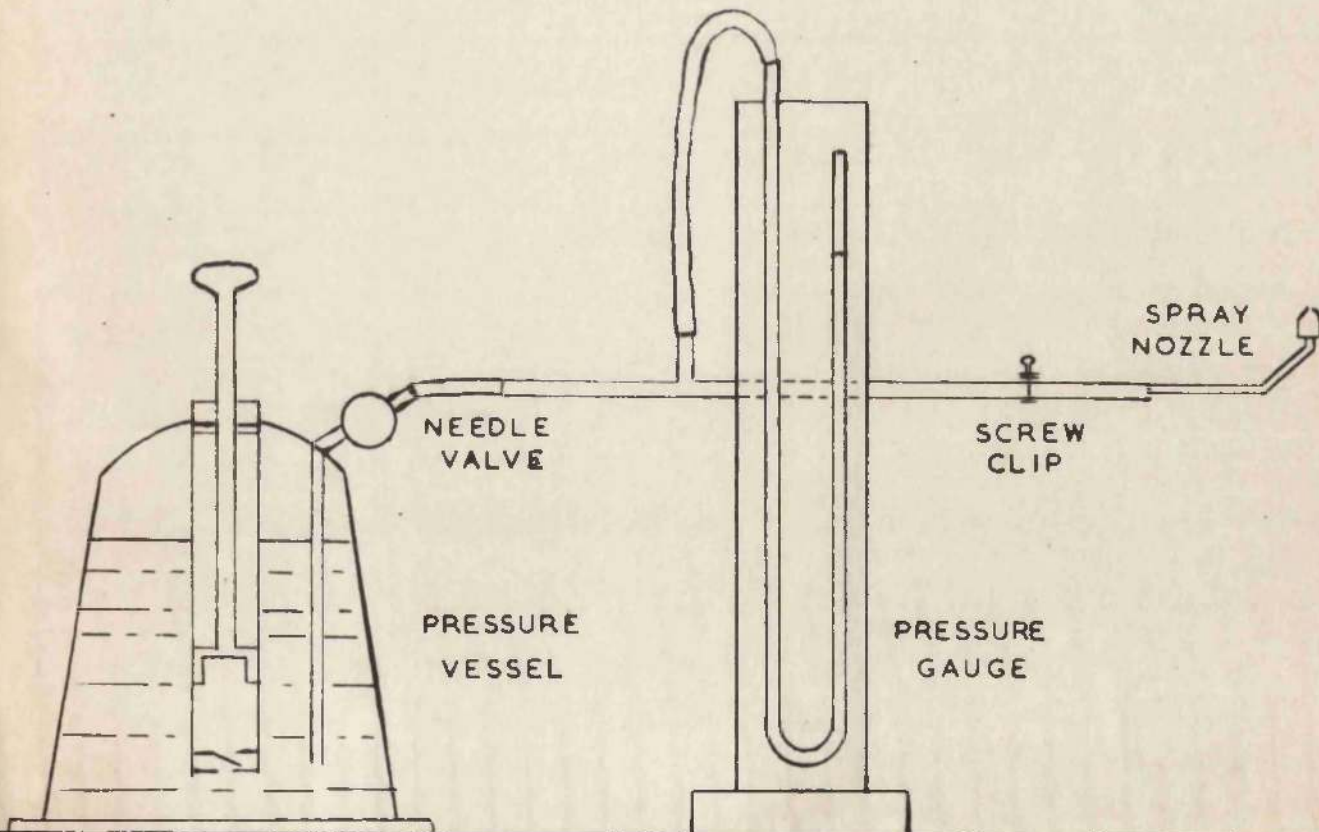


Table No. 1.

Characteristics of Different Spray Nozzles.

Nozzle No.	Orifice Diameter	Cone Angle of Spray	K
1	.0134 in.	30°	8.85
2	.0142 in.	30°	8.91
3	.016 in.	40°	11.58
4	.020 in.	90°	16.25

Table No. 2.

Effect of Different Collecting Media on Droplet Life.

Droplet Medium	Collecting Medium	
	Silicone Fluid MS 550	Hydraulic Fluid
Water	24 mins	12 mins
Water + 0.5% Lissapol NDB	18 mins	2 mins
Water + 0.5% Alcopol O	4 mins	Immediate aggregation and spreading.

30 - 80 lb./in.² to give the most reproducible figures for atomisation. The pressure vessel was not designed for pressures greater than 80 lb./in.²

Compressed-air-operated Spray.

A spray nozzle as shown in Fig. 2 is constructed from a stainless steel hypodermic needle and sheath to enable a fine water mist to be generated by low-pressure air. The apparatus used is shown in flow diagram form in Fig. 2. The air, supplied by a blower of variable output, passes along a length of pipe before passing through an orifice plate, which had been previously calibrated in cubic feet of air per minute, and finally enters the spray nozzle to atomise the water.

The water is supplied from a measuring cylinder contained in a pressure vessel. The pressure vessel is maintained at 7 lb./in.² by compressed air. The vessel is fitted with an escape valve set to 7 lb./in.² and mounted alongside a pressure gauge. The quantity of water reaching the nozzle is regulated by a calibrated needle valve.

Analysis of Results.

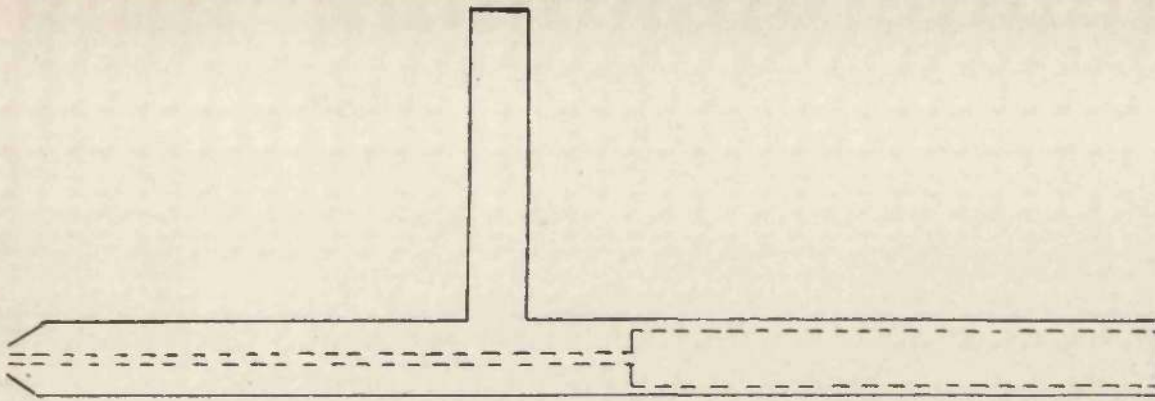
Liquid Pressure Spray.

The throughputs of the liquid pressure nozzles were measured by spraying downwards into a measuring cylinder. The procedure was repeated at twelve different pressures for each nozzle over the range 10 - 80 lb./in.²

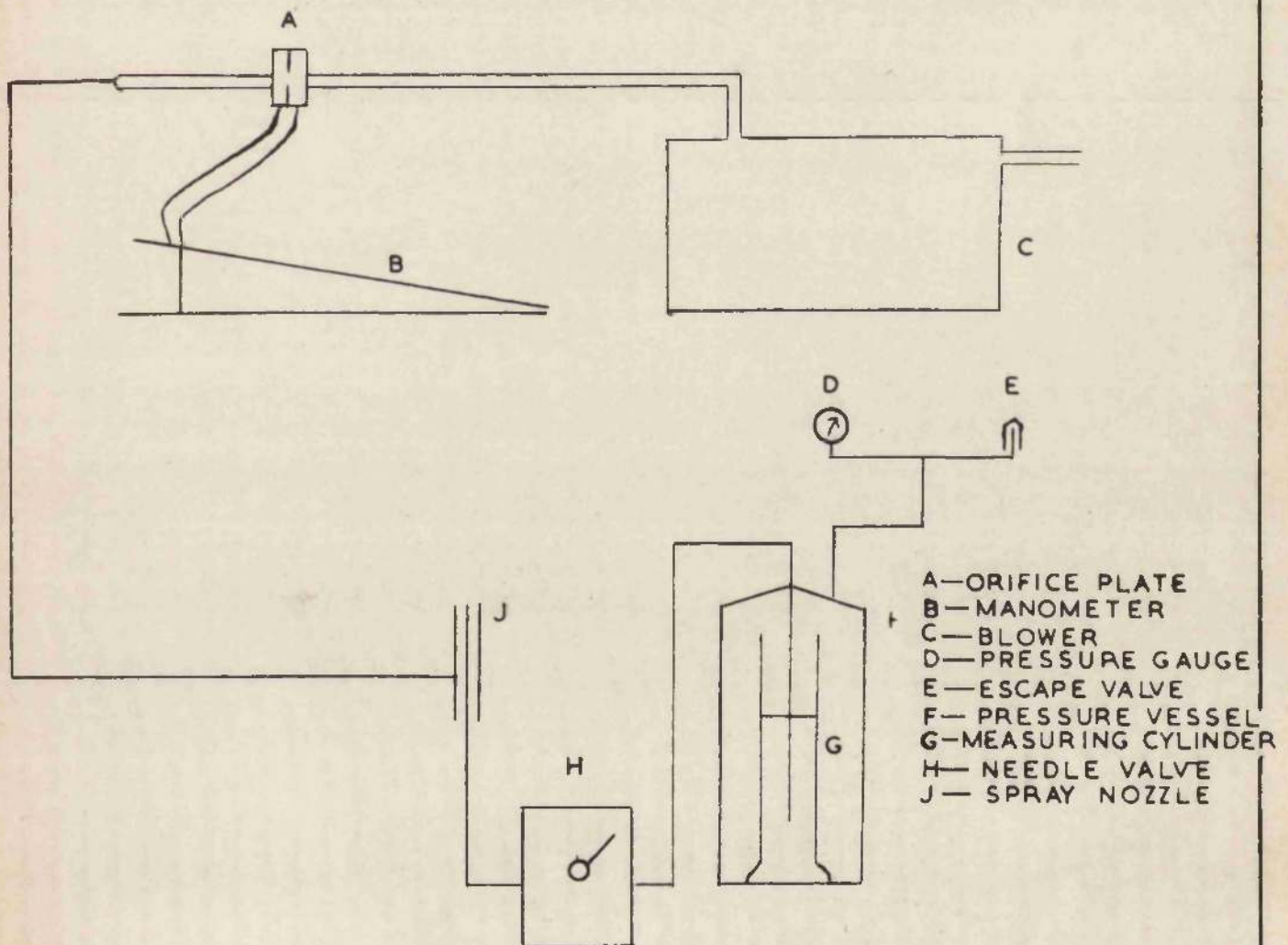
The experiment was repeated using a 0.5% aqueous solution of

FIG. No. 2

COMPRESSED-AIR-OPERATED SPRAY NOZZLE.



SPRAY UNIT



a S/A agent to form the spray.

The plot of throughput (V) of water in c.c.s/min against the square root of the pressure (\sqrt{P}) is shown for each of the four nozzles (Graph 2). In each case a straight line is obtained and this agrees with results obtained by Doble (40), who showed that for pressure sprays

$$V/\sqrt{P} = K.$$

The results for water and solutions of S/A agents are presented in Table 3 and show that the inclusion of the S/A agent in the spray solution does not alter the throughput. The value of K for each nozzle is shown in Table I.

Droplet-Size Distribution.

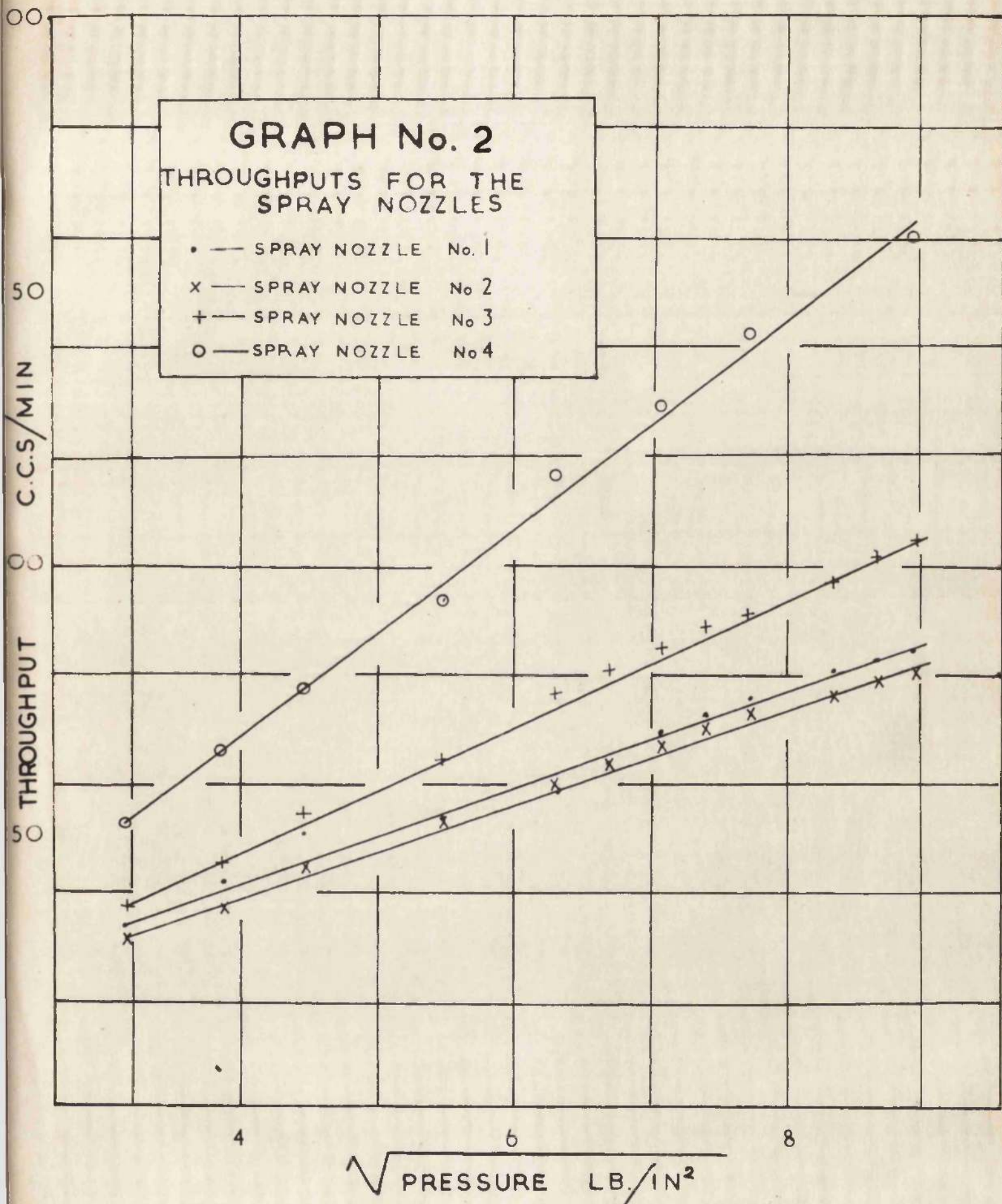
The droplet-size distribution characteristics of each spray were found to be reproducible, provided that a sufficiently large number of droplets was counted. Both types of sprays investigated had the advantage over those used by Massie (41) that the conditions could be accurately reproduced.

The sprays were sampled by clamping the spray nozzle on a stand on a large metal tray so that the spray was ejected vertically upwards, the throughput falling back onto the tray. The droplets were collected in a silicone oil film (42) on a microscope slide. The slide was passed through the body of the spray with a smooth horizontal action, with the silicone oil film facing the direction in which the droplets were rising. The sample was extracted from the spray at a distance of 18 in. from the nozzle. It was important

Table No. 3.

Variation of Throughput with Pressure.

Pressure lb./in. ²		c.c.s/min Throughput No. 1		c.c.s/min Throughput No. 2		c.c.s/min Throughput No. 3		c.c.s/min Throughput No. 4	
		Water	S/A agent	Water	S/A agent	Water	S/A agent	Water	S/A agent
P	\sqrt{P}								
10	3.162	33	35	31	30	37	37	52	54
15	3.873	41	38	36	36.5	45	42.5	66	68
20	4.472	45	42	44	43	54	49	77	82
30	5.476	53	53	52	53	64	62	93	102
40	6.325	58	63	59	63	76	74	116	118
45	6.71	63	67	63	66	80	79	124	128
50	7.071	69	69	66	68	84	92	129	133
55	7.416	72	73.5	69	73	85	97	136	137
60	7.747	75	75	72	72	90	98	142	148
70	8.365	80	80	75	75	96	98	152	152
75	8.66	82	83	78	79	101	106	160	160
80	8.945	84	86	79	81	104	108	160	161



to sample at the same height each time since atomisation increases with the distance from the spray nozzle.

To construct a distribution curve for a particular spray nozzle operating under certain conditions, it was necessary to count 400 droplets under the microscope. Since evaporation and aggregation of droplets was taking place all the time, only 50 droplets on each slide were counted and eight slides used in the construction of a size-distribution curve. The effect of evaporation and aggregation was more pronounced when a S/A agent was present in the sprays. The average life of the slide of droplets of 100 microns diameter is shown in Table 2 for a hydraulic fluid and for silicone fluid. Other oils showed the same behaviour to the droplets as hydraulic fluid.

It is obvious from the results (Table 2) that the silicone fluid is a much better medium for collecting the droplets than the hydraulic fluid and allows sufficient time to count 50 droplets before aggregation, evaporation, and spreading on the oil prevents true results being obtained.

Average Droplet Size.

When considering the fineness of different sprays it is useful to introduce some "mean droplet-size" which, while giving an indication of the degree of atomisation, still has a physical significance. The introduction of a mean droplet-size is equivalent to the replacement of the actual spray, composed of droplets of different sizes, by a fictitious spray in which all the droplets are of the same size, equal to the mean droplet-size. This spray may however still possess

certain features of the actual spray that are important from the point of view of dust suppression. The arithmetic mean diameter $\Sigma(\text{ND})/N$ is used to represent the spray.

Effect of Pressure on Droplet Size.

The four nozzles used with the liquid pressure spray were investigated to discover the range of droplet size obtainable by altering the pressure.

The droplet-size distribution curves for nozzle No.1 at different pressures with and without a S/A agent are shown in Graphs 3 and 4. The curves obtained showed an increase in atomisation as the pressure of the water was raised from 32 to 78 lb./in.² Similar curves were constructed for nozzles No.2, 3, and 4 and it was seen that the size-distribution curves, for the nozzles, for water alone at 62 and 78 lb./in.² lie close together indicating that no great improvement in atomisation is achieved by increasing the pressure above 62 lb/in.², i.e. the maximum atomisation achieved by increasing the pressure is reached at ca. 78 lb./in.² With the equipment used here any increase in pressure would not be expected to produce much change in atomisation.

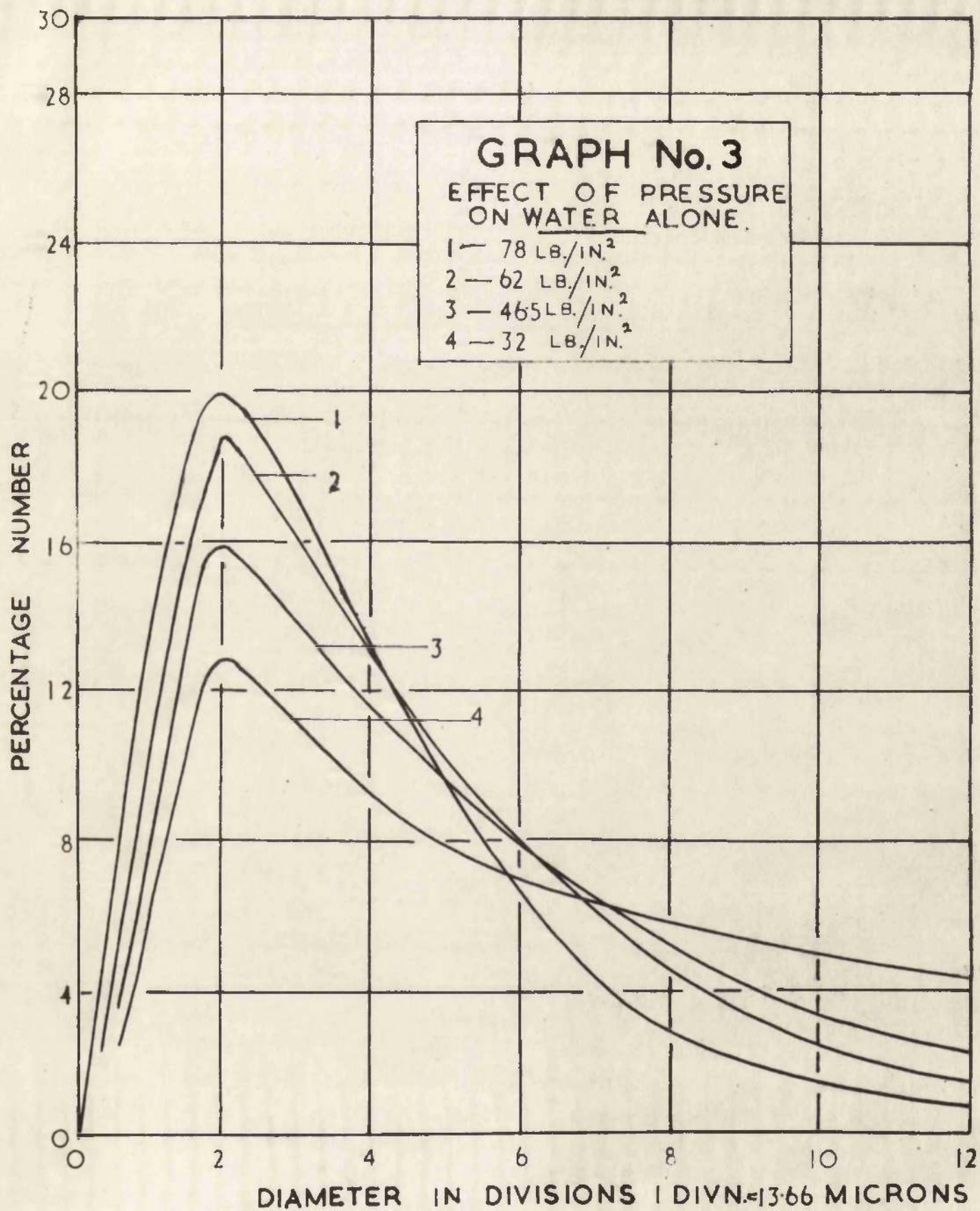
Effect of Orifice Diameter on Droplet Size.

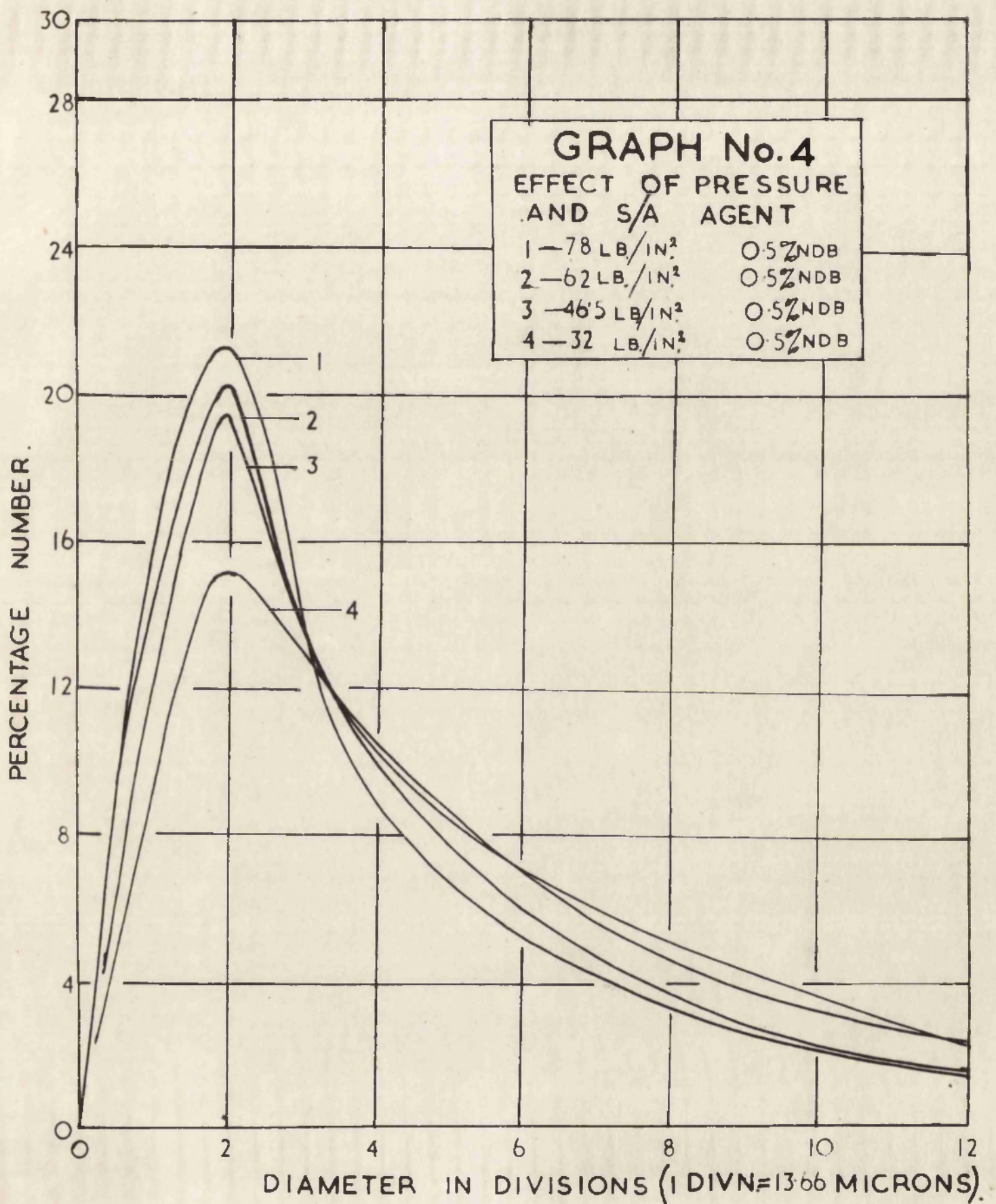
It would be expected that for nozzles No. 3 and No. 4, where the throughput is greater, the average droplet size would be increased for the same pressure. This is not so, however, as can be seen by inspecting Table 4, which shows the average droplet size at different pressures. As the orifice diameter size increases to 0.016 in. for

Table No. 4.

The Effect of Pressure and S/A Agent on Droplet Size.

Nozzle No.	Pressure lb./in. ²	S/A Agent	Microns Average Droplet Size
1	78	--	47.8
	62	--	58.2
	46.5	--	68.5
	32	--	89.8
	78	0.5% NDB	44.1
	62	0.5% NDB	49.3
	46.5	0.5% NDB	52.0
	32	0.5% NDB	66.8
2	78	--	43.3
	62	--	44.4
	46.5	--	52.5
	21	--	80
	78	0.5% NDB	37.7
	62	0.5% NDB	38
	46.5	0.5% NDB	44.8
	21	0.5% NDB	55.7
3	78	--	45
	62	--	49
	32	--	53.8
	78	0.5% NDB	41
	62	0.5% NDB	43.5
	32	0.5% NDB	51.8
4	78	--	42.7
	62	--	52.5
	32	--	58.6
	78	0.5% NDB	40.8
	62	0.5% NDB	43.5
	32	0.5% NDB	45





nozzle No.3 and 0.020 in. for nozzle No.4 the average droplet size becomes smaller. This is explained by the angle of spray being greater for nozzles No.3 and No.4 than for nozzles No.1 and No.2 (Table I). A greater air surface is therefore presented to the spray and more effective atomisation takes place. An increase in spray dispersion has normally a beneficial effect on atomisation, by increasing the amount of air involved in the disintegration process, and by decreasing the density of the spray (ratio of liquid to air by volume in the cross section of the spray, which prevents collision of droplets) The effect of pressure on the cone angle is not appreciable provided that the pressures are already high enough to produce a fully developed spray cone. In a swirl atomiser of the type used the ratio of mean tangential velocity to mean axial velocity determines the spray cone angle. The inclusion of a S/A agent in the spray solution did not alter the cone angle of the spray.

Surface-Active Agents.

Wetting agents or detergents are chemical substances containing polar molecules, soluble in water at one pole (hydrophilic) and insoluble at the other (hydrophobic). The hydrophilic poles are made up of radicals of cyclic hydrocarbons (aromatic), straight-chain aliphatic, or combinations of both, whilst the principal hydrophilic radicals are the groups $-\text{OH}$, $-\text{COOH}$, $-\text{SO}_2\text{Cl}$, $-\text{SO}_3\text{H}$ or $-\text{SO}_3\text{Na}$. In the wetting-agent solution the molecules orient themselves with the hydrophilic end of the molecule in the interior of the drop and the hydrophobic end at the surface. In this way they mass themselves

at the interphase boundary, .e.g. water-air.

The surface tension of such solutions decreases, with increasing concentrations of the wetting agent, to a minimum value which depends on the kind of product used. Even when the contact time is relatively long, the surface tension of the solution can only be an indication, as theory and practice show, that the wetting power is not solely a function of the surface tension, but the nature and also the state of the surface to be wetted have their importance.

Chemically there are two classes of S/A agents, the ionic and the non-ionic. The non-ionic class has non-ionisable end-groups, with a high affinity for water usually containing a number of oxygen, nitrogen, or sulphur atoms. The ionogenic class of agents has two main divisions. If the portion of the molecule with the low affinity for water is included in the anion in aqueous solution, the substance is termed anionic. The cationic S/A agents form a cation containing the low affinity portion of the molecule.

The S/A agents used in the atomisation and dust suppression work were selected from a number of the better known types. The commercial name of the compound used is given in brackets.

- Type 1. Sulphated vegetable oils (Calsolene Oil HS)
2. Sulphated fatty alcohols (Lissapol C)
3. Sulphonated alkyl amylsulphonates (Perminal BS)
4. Long-chain amide sulphonates (Lissapol LS)
5. Sulphosuccinic esters (Alcopol O)
6. Esters and ethers (Lissapol N, Labrol W)
7. Quaternary ammonium compounds (Fixapol C)

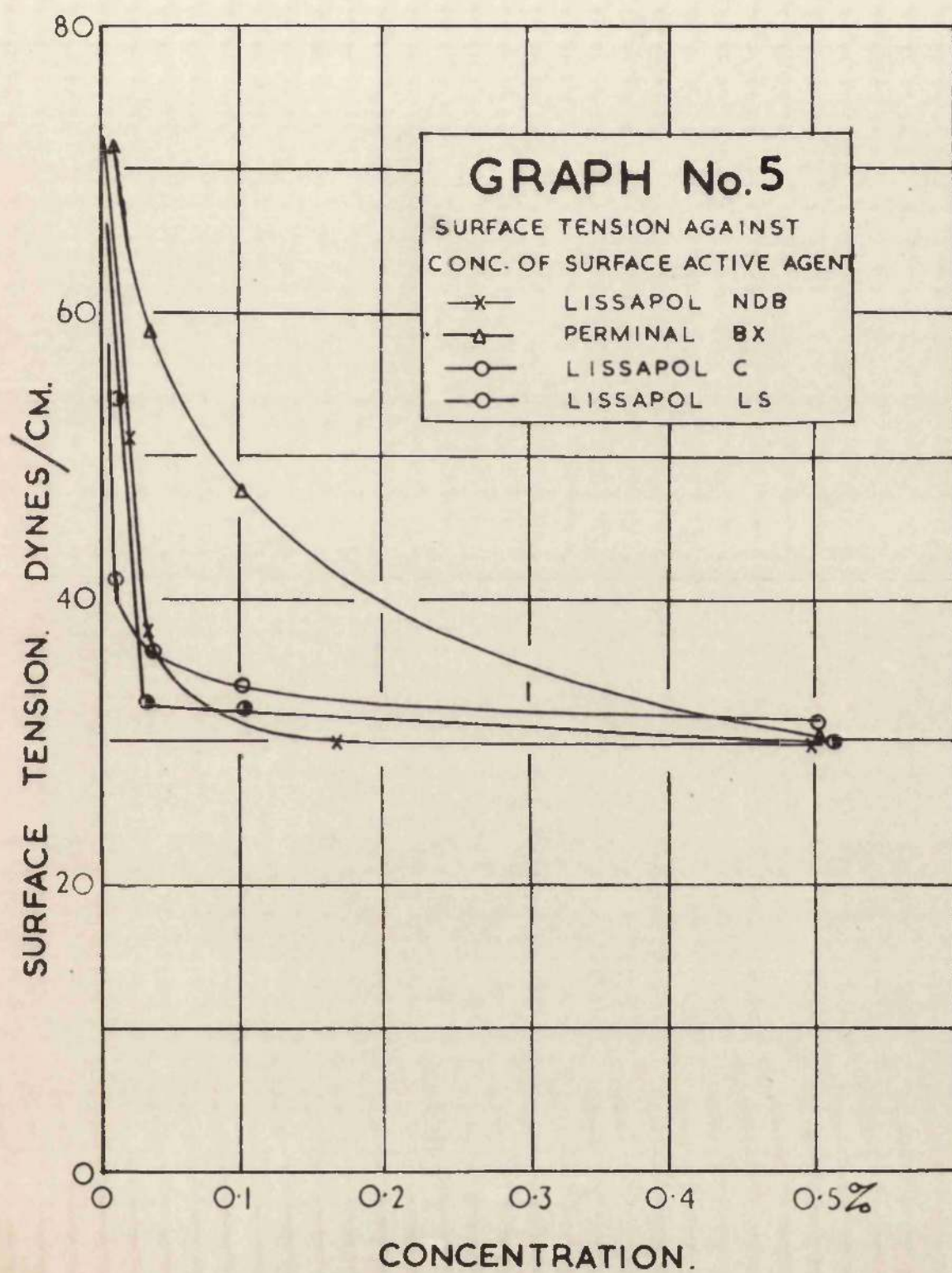
The above compounds were chosen to include anionic, cationic, and

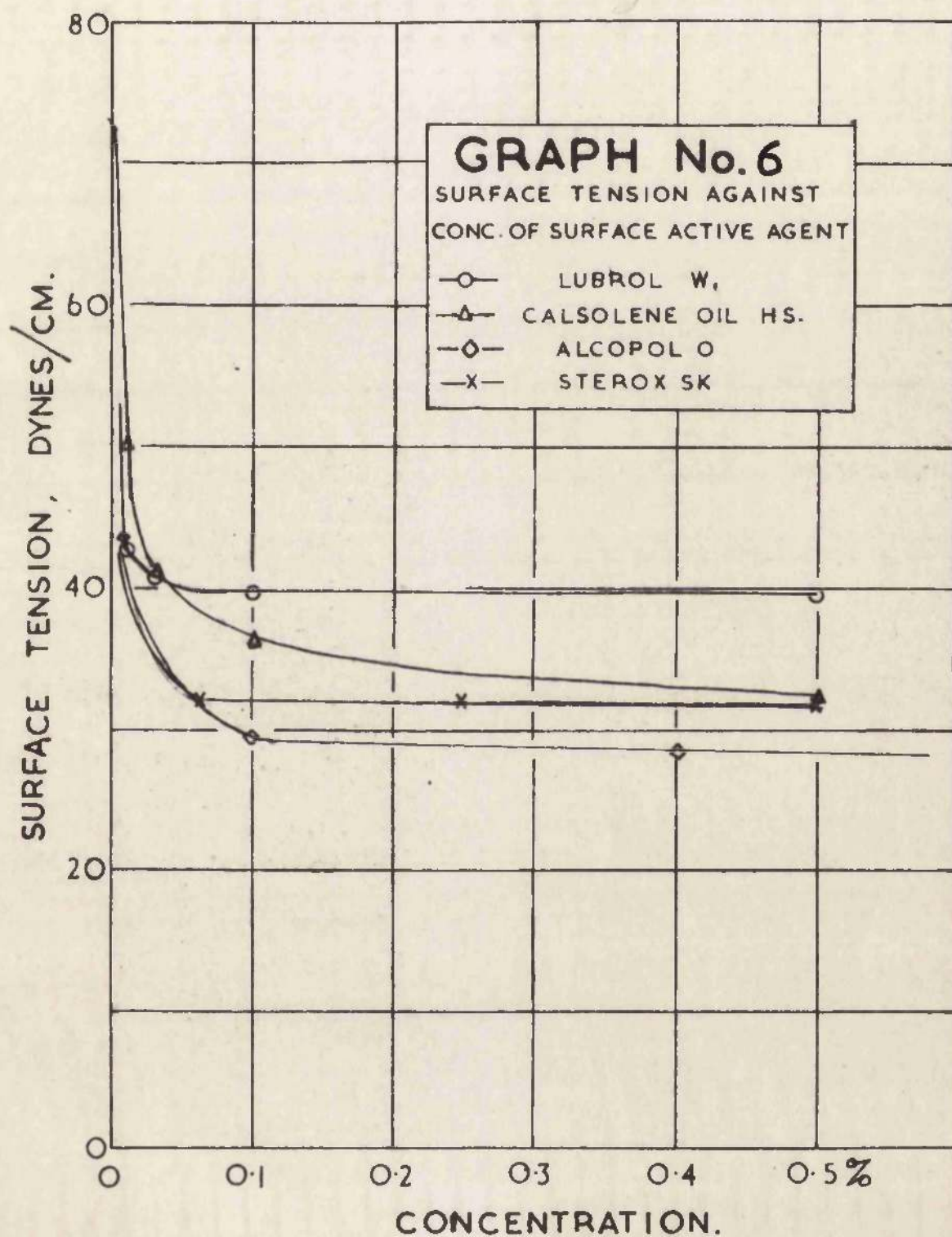
non-ionic S/A agents.

Lissapol NDB (a dilution of Lissapol N, an alkylated ethylene oxide condensate) was used in the initial experiments to show the effect of the alteration of surface tension on the characteristics of a spray. This non-ionic S/A agent is manufactured by I.C.I. Ltd. and is recommended for the suppression of dust in mines (43). The variation of surface tension of an aqueous solution of Lissapol NDB with concentration is shown in Graph 5. The surface tension of the solution drops steeply to 0.15% Lissapol NDB, corresponding to a surface tension of 30 dynes/cm. The concentration chosen for use in the formation of sprays was 0.5% which gives a solution of minimum surface tension with excess Lissapol NDB present.

The size distribution curves obtained for sprays formed from a 0.5% solution of Lissapol NDB (Graph 4) show a variation from those formed from water alone. The greatest variation is obtained at low pressures, i.e. at 32 and 46.5 lb./in.², while at 62 and 78 lb./in.² the increase in atomisation is not so great. This is as might be expected, since it is reasonable to assume that as the forces taking an active part in the disintegration of a liquid jet increase and as the energy available for the formation of the droplet increases in relation to the energy actually needed, then the effect of the liquid properties (viscosity, surface tension etc.) on atomisation will be reduced.

The increase in atomisation due to the inclusion of the S/A agent in the spray solution is shown in the average droplet size produced





(Table 4), the increase being more pronounced at lower pressures.

Effect of Concentration of S/A Agent.

Sprays were formed from different concentrations of Lissapol NDB, the concentrations being chosen to give a range of surface tension and also to give different concentrations at the same surface tension. The concentrations used were 0.02%, 0.2%, 0.5% and 1% and the pressure used to form the spray was 46.5lb./in.² This pressure was chosen because the surface tension had been found to have a greater effect on the size distribution of the droplets formed at this pressure than at higher pressures, for the reasons already discussed (p.26). The effect of varying the concentrations of the S/A agent was investigated for nozzle No.1 and the results obtained (Graph 7 and Table 5) illustrate the improvement with decrease in surface tension. The greatest atomisation occurs at the highest concentration, 1% Lissapol NDB. The distribution curves for 0.5% and 0.2% Lissapol NDB solution are seen to be in good agreement as would be expected since both these concentrations result in approximately the same surface tension.

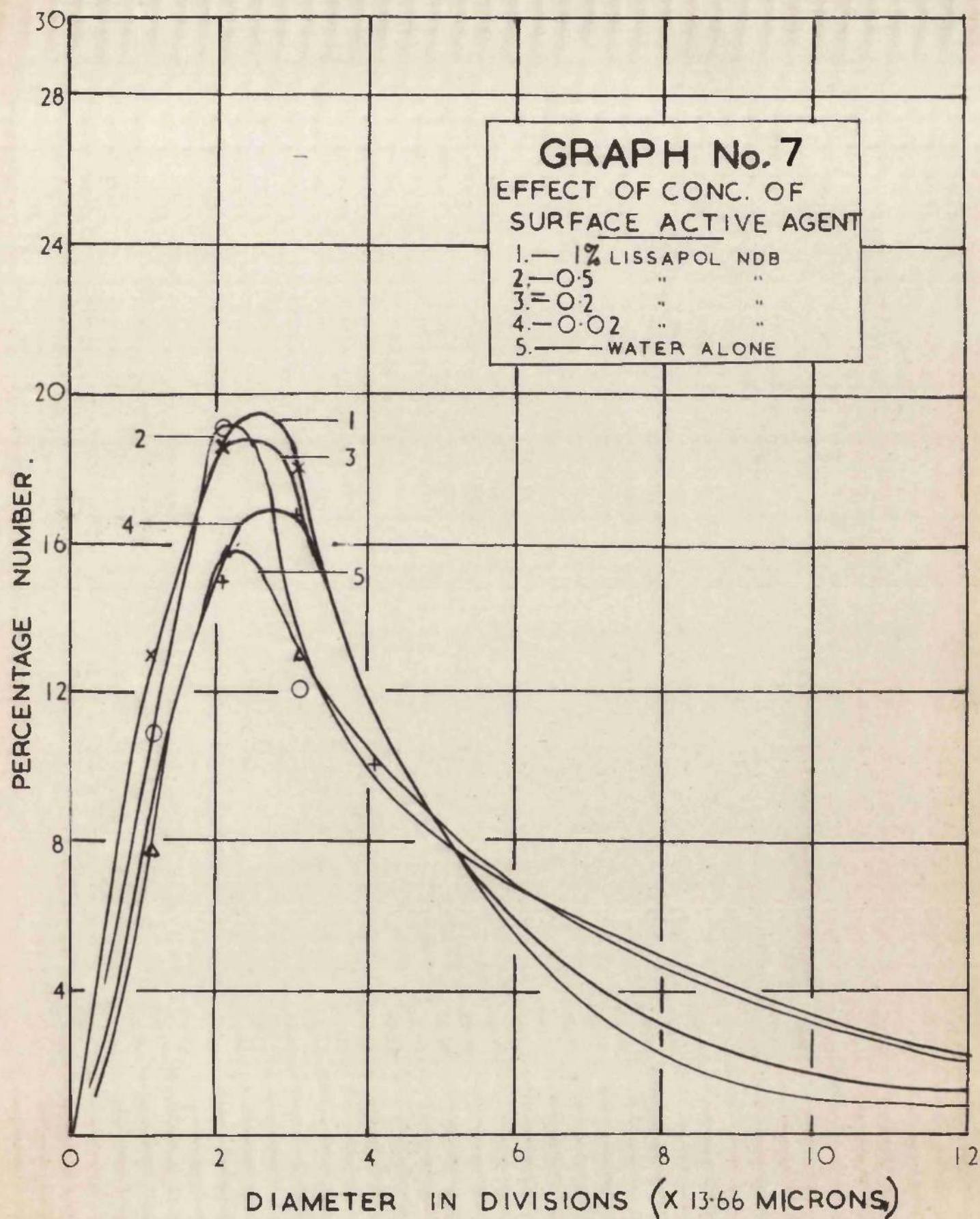
The curve for 0.02% solution of Lissapol NDB shows an increase in atomisation over that of water alone, but the increase is not so great as that experienced with the higher concentrations of S/A agent.

This is again what would be expected, since the surface tension of the 0.02% solution is intermediate between that of water and that of 0.2% Lissapol NDB solution. This effect is also shown in Table 5 where the average droplet sizes of the sprays formed from the

Table No. 5.

Effect of Concentration of S/A Agent on Average Droplet Size.

Nozzle No.	Pressure lb./in. ²	Conc. of S/A agent	Surface Tension dynes/cm	<u>Microns</u> Average Droplet Size
1	46.5	1% NDB	29	51.3
	46.5	0.5% NDB	29	51.0
	46.5	0.2% NDB	30	56.0
	46.5	0.02% NDB	50	70.5
	46.5	water	72.8	64.5



different concentrations of the S/A agent are presented.

If one considers the range of droplet size produced in any one spray and the effect of the liquid properties on that range, it can be seen that there is little change in the mode of the size distribution curve with variation in surface tension, although the height of the curve may vary (cf. Graphs 3 & 4.). On the other hand the size of the biggest droplets encountered in a spray will be closely related to the surface tension of the solution used. It may be generally stated that high surface tension or low pressure promotes the formation of bigger droplets and decreases the degree of spray uniformity.

Effect of other S/A Agents.

The work on the effect of Lissapol NDB on spray characteristics was repeated with spray nozzle No.1 for the other S/A agents used in the dust suppression work.

It was found, as with Lissapol NDB, that the S/A agent did not affect the throughput of the nozzle nor alter the cone angle of the spray. Size distribution curves were constructed and average droplet sizes calculated for the different S/A agents at different water pressures with the same nozzle (No.1).

The values obtained for the different droplet sizes are presented in Table 6. It can be seen that the atomisation increases with (i) pressure and (ii) the use of a small concentration of a S/A agent.

The effect of the different S/A agents appears to be the same showing that surface tension is the only factor involved in the atomisation, the class of S/A agent being unimportant. The exception to this is Fixanol C which gives a lower efficiency of atomisation.

These results show that it is possible to carry out spraying runs on the dust cloud to compare the effect of the different classes of S/A agent since the degree of atomisation of the solutions of the different S/A agents are the same within experimental error.

The Compressed-air-operated Spray.

The results for the compressed-air-operated spray will not be reported in the same detail as those for the hydraulic spray since

Table No. 6.

Effect of Different S/A Agents on Atomisation.

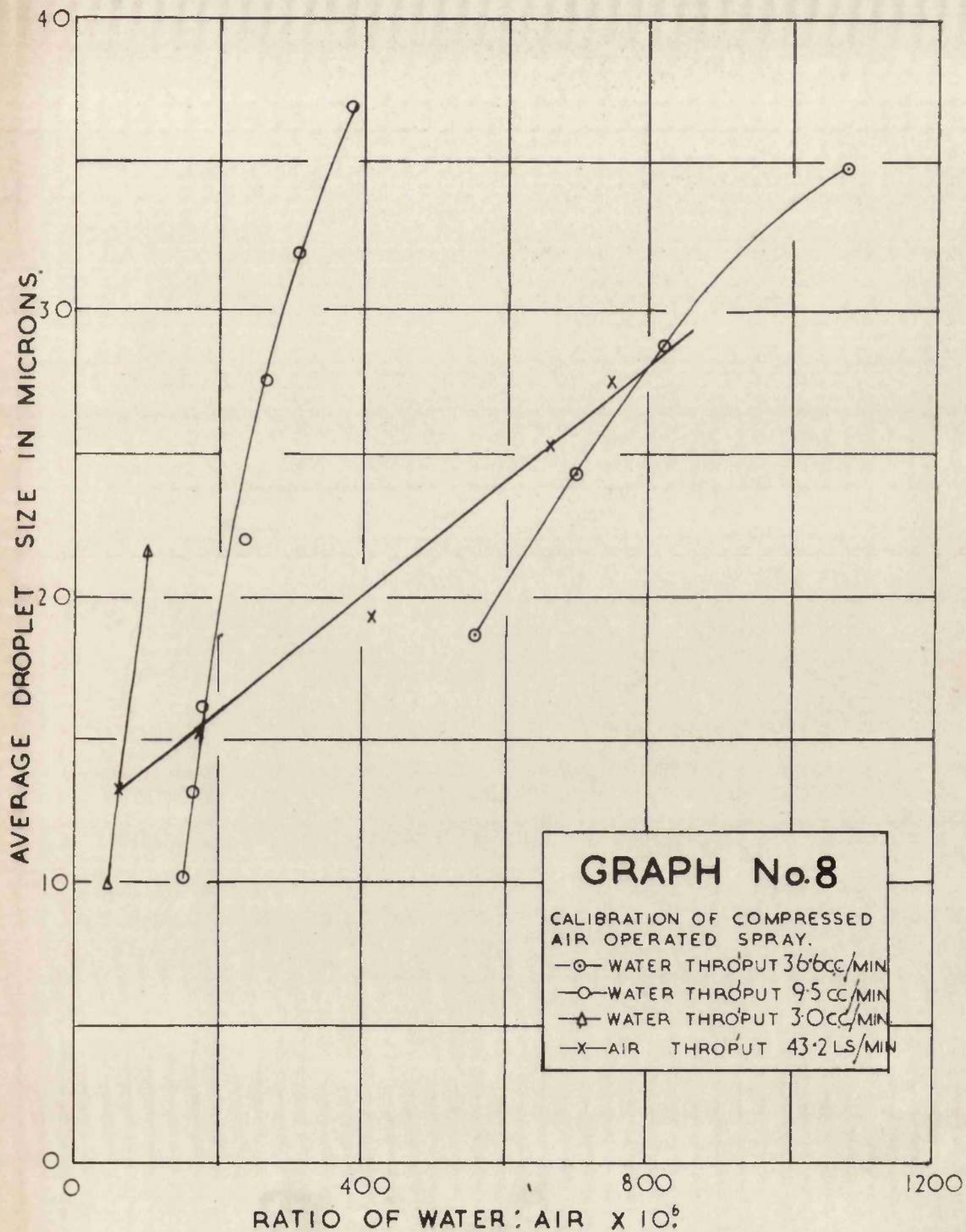
S/A Agent	Average Droplet Size (Microns) Pressure lb./in. ²			
	32	46.5	62	78
Water	90	68.5	58	48
Lissapol NDB	66.5	52	49	44
Fixanol C	79	58	56	49
Aleopol O(aq)	67	57	53.5	44.5
Aleopol O(al)	64	55.5	51.5	47.5
Sterox SK	66.5	56	54	49
Lubrol W	64.5	56	46.5	49
Calcolene Oil HS	67	67	53.5	50
Usappol C	65.5	57.5	49.5	44

no spraying runs were carried out to estimate its efficiency in suppressing dust. Compressed air sprays have been shown to be the most effective type in suppressing dust at its source (44, 45). Its action is twofold:-

- (1) The dust particles are knocked down by the spray droplets.
- (2) The air used in atomisation dilutes the dust cloud and gives the impression that the efficiency of dust removal is high.

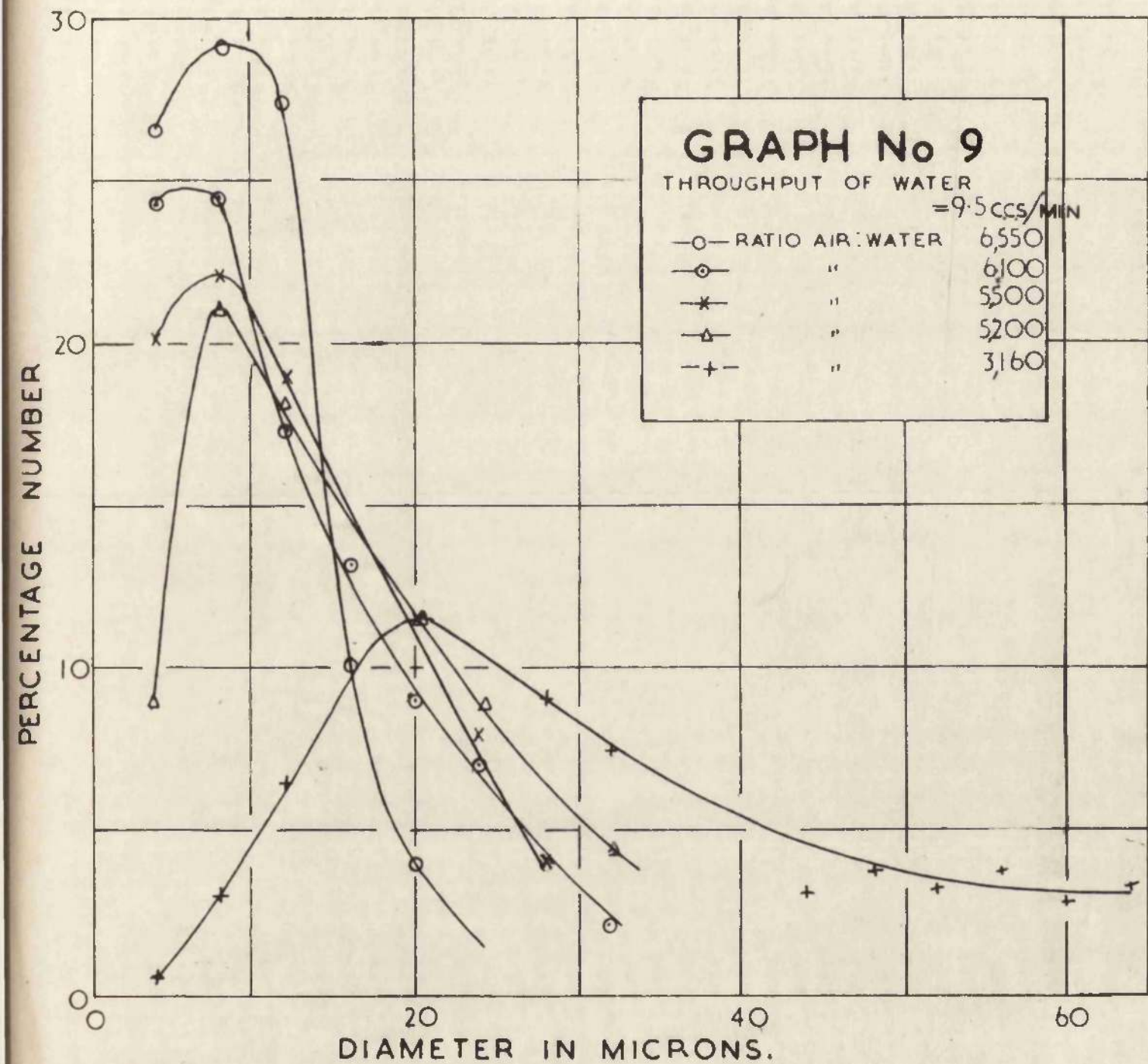
The spray droplets formed by the air spray were sampled in the same way as for the hydraulic spray, 400 droplets being sized on eight slides coated with hydraulic fluid.

The values for the average droplet size obtained were plotted against the ratio of air to water leaving the spray nozzle. The plot obtained is shown in Graph 8. It can be seen that it is possible to obtain a family of curves which will enable different conditions of water and air throughput to be selected to produce a spray with a known average droplet size. The atomisation obtained by the air spray is much greater than that obtained by the water pressure spray, but to achieve this high atomisation the ratio of air to water used has to be very high. The slope of the line through the points of equal water throughput is seen to decrease as the water throughput increases. This is in agreement with the results obtained with hydraulic sprays, namely, that as the energy supplied to the process of atomisation increases in relation to the energy actually required, no great improvement in atomisation results.



Size distribution curves obtained for a throughput of 9.5 c.c.s/min show the range of droplet size obtainable using this type of spray nozzle (Graph 9). No droplets smaller than 4 microns are detected because of the high rate of evaporation of such small droplets.

It was decided not to use the compressed-air-operated spray in the dust suppression work since the large volume of air used in the atomisation process would introduce complications difficult to estimate.



Conclusions.

Two types of water sprays, (1) hydraulic or water-pressure and (2) compressed-air-operated, have been developed and calibrated. They were found to give sprays with reproducible size distribution and average droplet size.

The compressed-air-operated spray was capable of producing much finer droplets but the volume of air used in the process of atomisation rendered it unsuitable for use in the dust chamber.

The water-pressure spray was investigated thoroughly and the atomisation was found to increase when (1) the pressure of the water was increased, (2) the orifice diameter of the spray was increased over the range investigated, and (3) a S/A agent was added to the spray solution. The effect was more pronounced at lower pressure.

The atomisation was found to be independent of the type of S/A agent used. An apparent exception to this was Fixanol C, which did not give as good atomisation as the other S/A agents.

The atomisation increased with increase in concentration for Lissapol NDB. A slight increase in atomisation of 1% solution was detected over that of the 0.5% and 0.2% solutions of Lissapol NDB which have the same surface tension.

The increase was not great and could be due to experimental error.

SECTION 2The Development of Apparatus and Experimental Method.

The photometric method of estimating concentration, developed by Wagner (46) and Richardson (47), in which light energy is measured by a sensitive photometer, may be adapted to the determination of the specific surface of a powder in suspension by a single photometric reading, or, alternatively, to the determination of the size frequency of the material from a series of readings taken over a period of time as the sample settles. The light traversing the suspension is measured by a photometer and the reduction in light intensity is related to the specific surface of the particles in the suspension in such a way that the mean projected area of a particle of any shape in random motion is equal to one quarter of the geometric surface of the particles. Berkelhamer (48) used a device based on this principle to measure rates of sedimentation, as did Schweyer (49) and Skinner et al. (50). Davies (51) and First & Silverman (52) followed the sedimentation of a dust by collecting samples on microscope slides during the sedimentation and measuring the particles.

The apparatus used in the work described here incorporated modifications which allowed measurements of the concentration and size distribution of the dust cloud to be made. The photoelectric cell system used was similar to that employed by Massie (41). The light extinction method gave results on a comparative basis for the measurement of the dust cloud. To obtain information on the size

distribution of the dust and the concentration in particles per cubic centimeter, a T.P. was built into the apparatus. The T.P. head could be lowered to any depth in the dust chamber, a sample of the dust cloud withdrawn, and the microscopic cover circles mounted on a slide for examination.

Dust Sedimentation Chamber.

The chamber was much larger than that used by Massie(41), which had a cubic capacity of 12,000ccs, and was built in the form of a cylinder, 5 feet in height and 18 inches in diameter. This size and shape was chosen after preliminary experiments and has the following advantages:-

1. The wall effects on the dust in suspension in the chamber were reduced.
2. A sample of the dust could be withdrawn by means of the T.P. without causing a serious decrease in the concentration.
3. Sprays with larger throughputs and spray angles could be used (i.e. nearer to actual mining conditions) without too great a loss in efficiency owing to droplets striking the sides of the chamber.
4. The amount of dead space was reduced by making the chamber cylindrical rather than square.

Construction of the Chamber.

The top of the chamber was fitted with a circular cover and a conical base fitted to assist drainage. Both of these were fitted with rubber gaskets and held in position by eight bolts and

winged nuts.

The chamber was coated internally with matt black paint to reduce light reflection and suspended from a welded frame structure by four lugs situated half-way down the chamber. Care was taken to hang the chamber truly vertical before it was bolted into position on the frame. A small observation window was built on the front of the chamber to permit inspection of the dust cloud and spray. A two-bladed fan, length 15 inches, was made from aluminium sheet and fitted through an aperture in the roof. A drawing of the chamber is shown in Fig. 3 and a photograph shown in Plate 1.

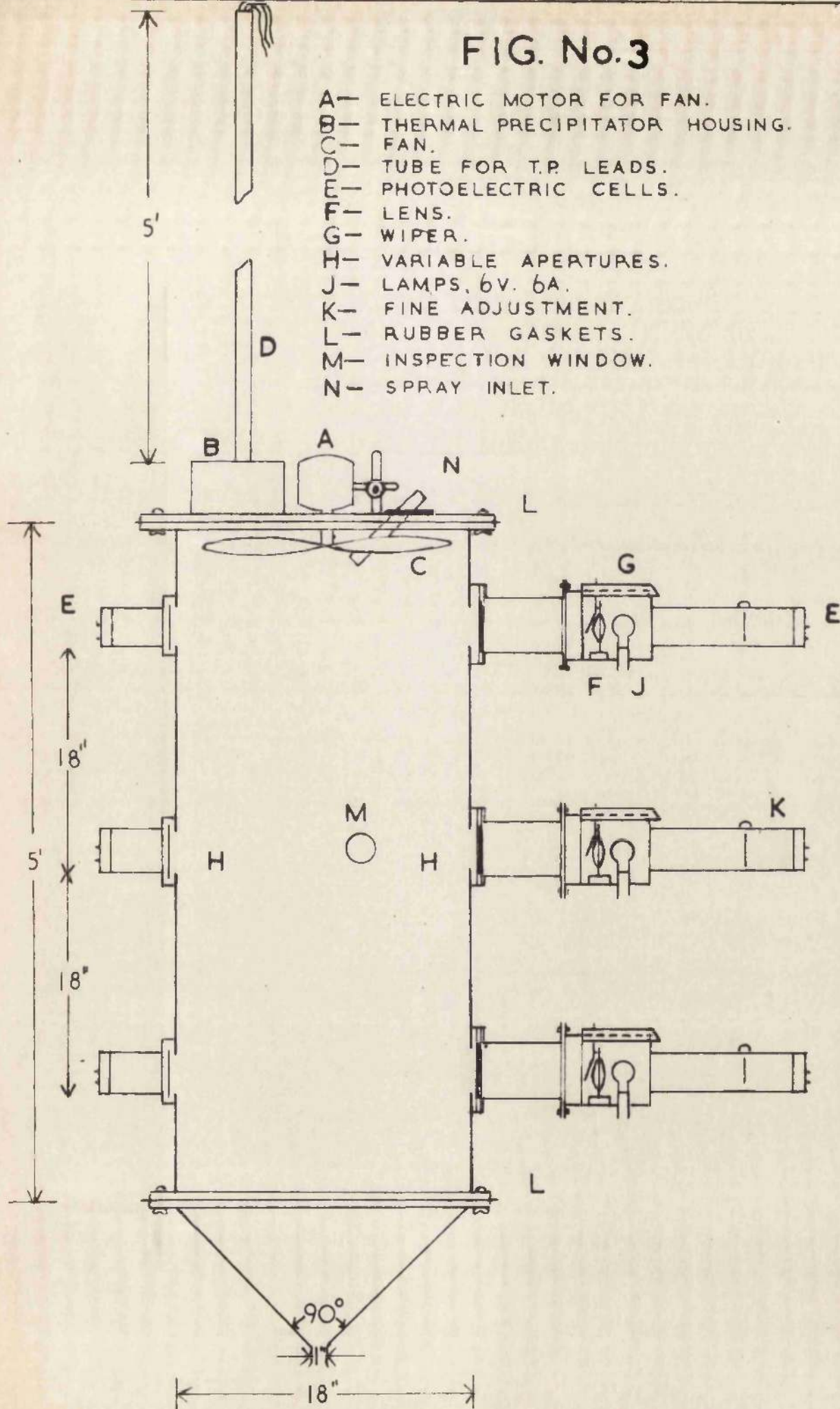
The Photoelectric Cell Units.

The design of the photoelectric cell units was based upon that used by Smellie (53) to measure the dispersabilities of mine stone dusts and further developed by Cumming, Rumford and Wright (54) for experiments on the dust produced by various types of tetryl. The apparatus was modified by Massie (41) to enable small concentrations of dust to be estimated. Three photoelectric cell units were spaced at intervals down the length of the chamber to record the concentration at different depths in the chamber and also to act as a check on each other.

A photoelectric cell unit is shown in Fig. 4. The lamp housing (A) contains a 6V, 6A automobile headlamp (B) and is attached to a compartment (C) which is bolted onto the dust chamber. This compartment (C) helps to prevent the deposition of dust on the lens by separating the lens from the dust chamber. The lamp is supplied

FIG. No.3

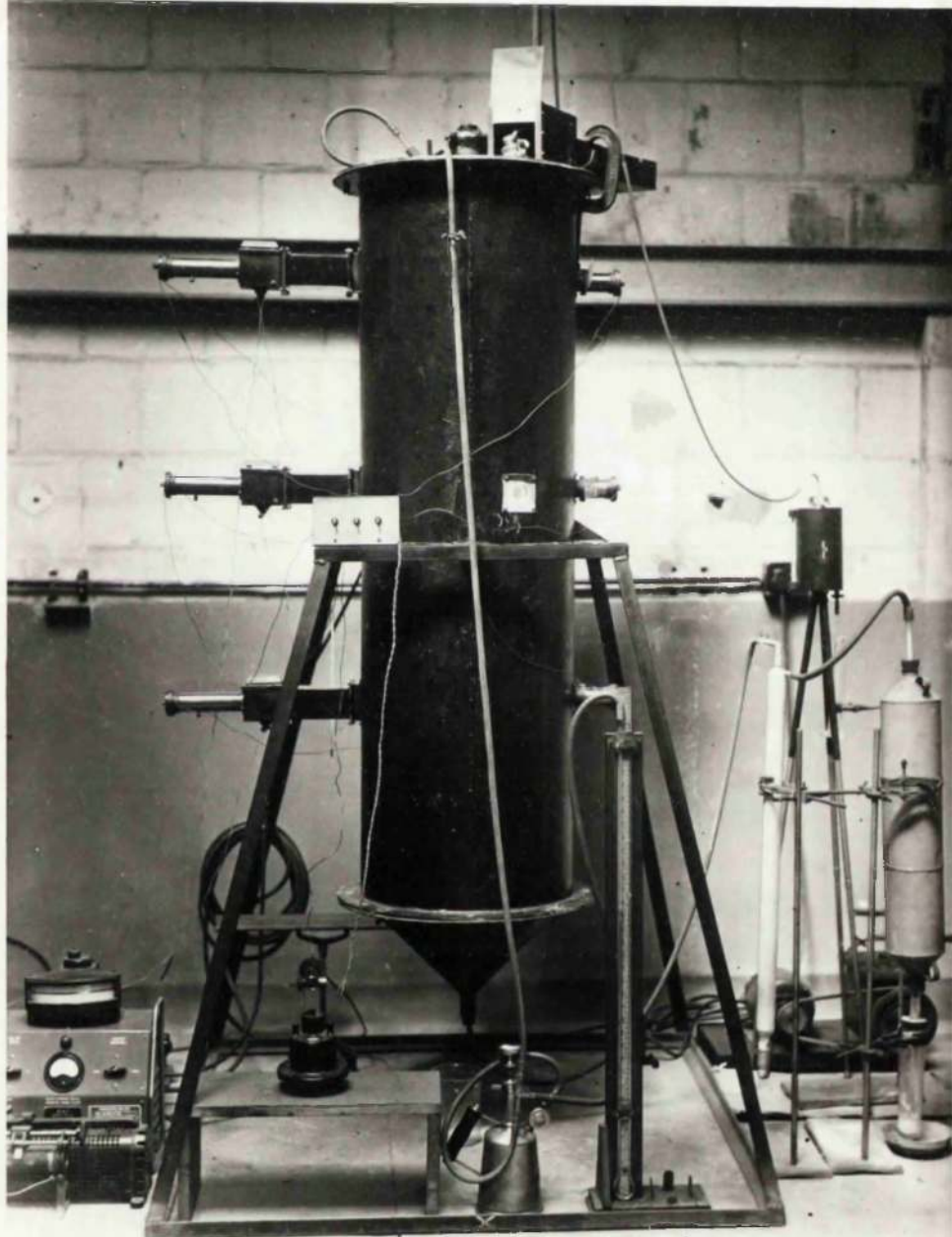
- A— ELECTRIC MOTOR FOR FAN.
- B— THERMAL PRECIPITATOR HOUSING.
- C— FAN.
- D— TUBE FOR T.P. LEADS.
- E— PHOTOELECTRIC CELLS.
- F— LENS.
- G— WIPER.
- H— VARIABLE APERTURES.
- J— LAMPS, 6V. 6A.
- K— FINE ADJUSTMENT.
- L— RUBBER GASKETS.
- M— INSPECTION WINDOW.
- N— SPRAY INLET.



DUST SEDIMENTATION

APPARATUS

Plate No. 1.



from a 12V accumulator and the light from the 36W lamp is transmitted through the chamber by a collimating lens (D) which concentrates the beam and makes it parallel. No windows were built into the side of the chamber but a clearance was left at the entry and exit of the light beam to the chamber. The lens can be cleaned while the apparatus is in use by means of a wiper (E) which can be rotated over the surface of the lens. Opposite the lens is fitted a barrier layer photoelectric cell (F) and opposite the lamp is fitted a similar and compensating cell (G) balanced with the first. The photocells are connected in opposition across a d'Arsonval mirror type galvanometer having a resistance of 57 ohms and a sensitivity of 332 mm per microamp at one metre. The amount of light reaching the cells can be adjusted by two rectangular pieces of metal (H) which have different diameter apertures drilled in them. The cells are housed in cylinders which exclude stray light from the observation window in the front of the chamber. A zero reading is obtained on the galvanometer by use of a fine adjustment (J) consisting of a thin strip of blackened foil (11 mm wide) which may be rotated in the path of the light beam. In compartment (C) a holder is fitted to support neutral density filters of various degrees of transmission. The circuit diagram for the three photoelectric cell systems is shown in Fig. 5.

Thermal Precipitator Unit.

The structure built into the dust chamber to accommodate the T.P. and to allow it to be lowered to any depth in the chamber is shown in Fig. 3. It consists of five feet of copper tubing, one inch

FIG. No. 4

PHOTOELECTRIC CELL UNIT

NOT TO
SCALE

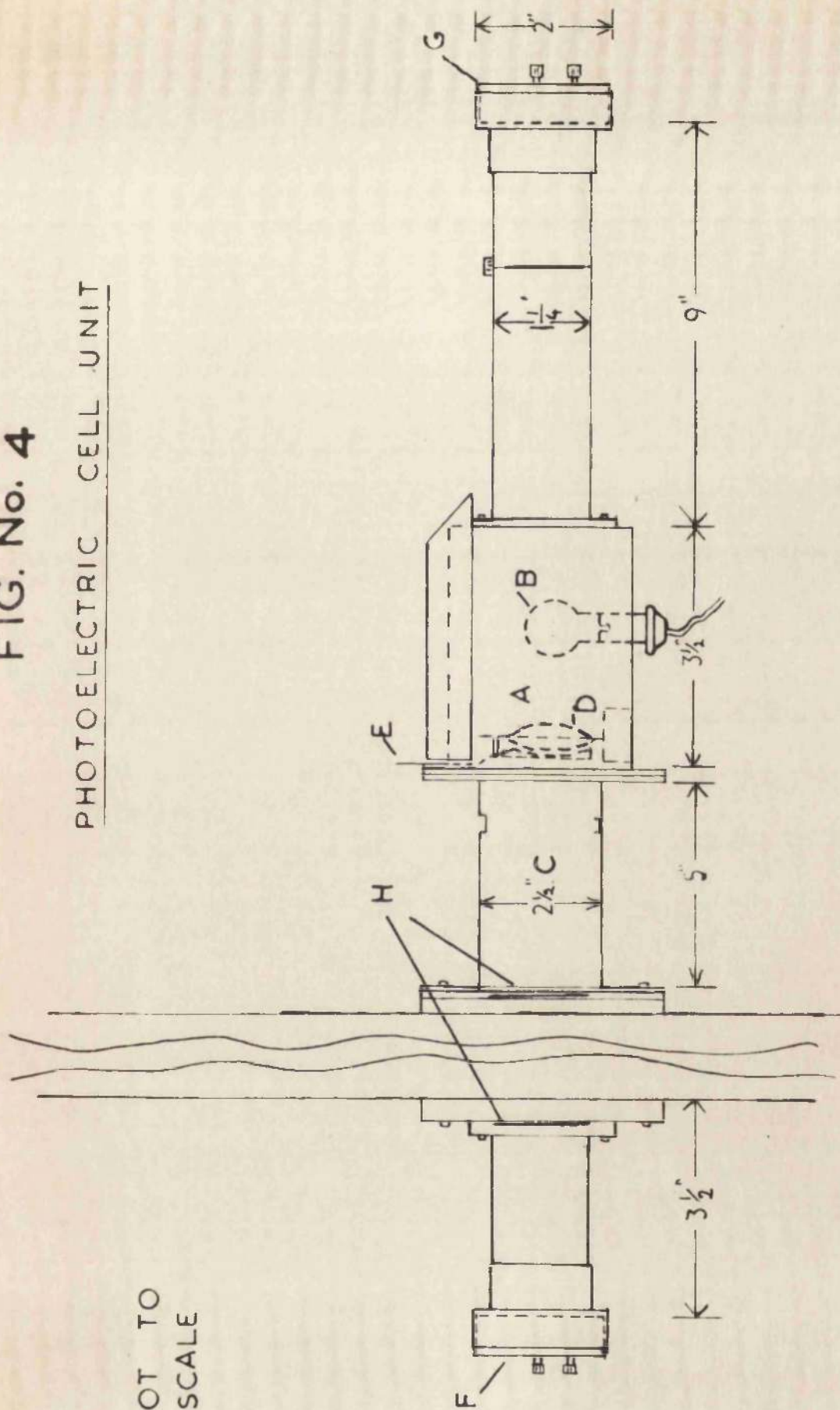
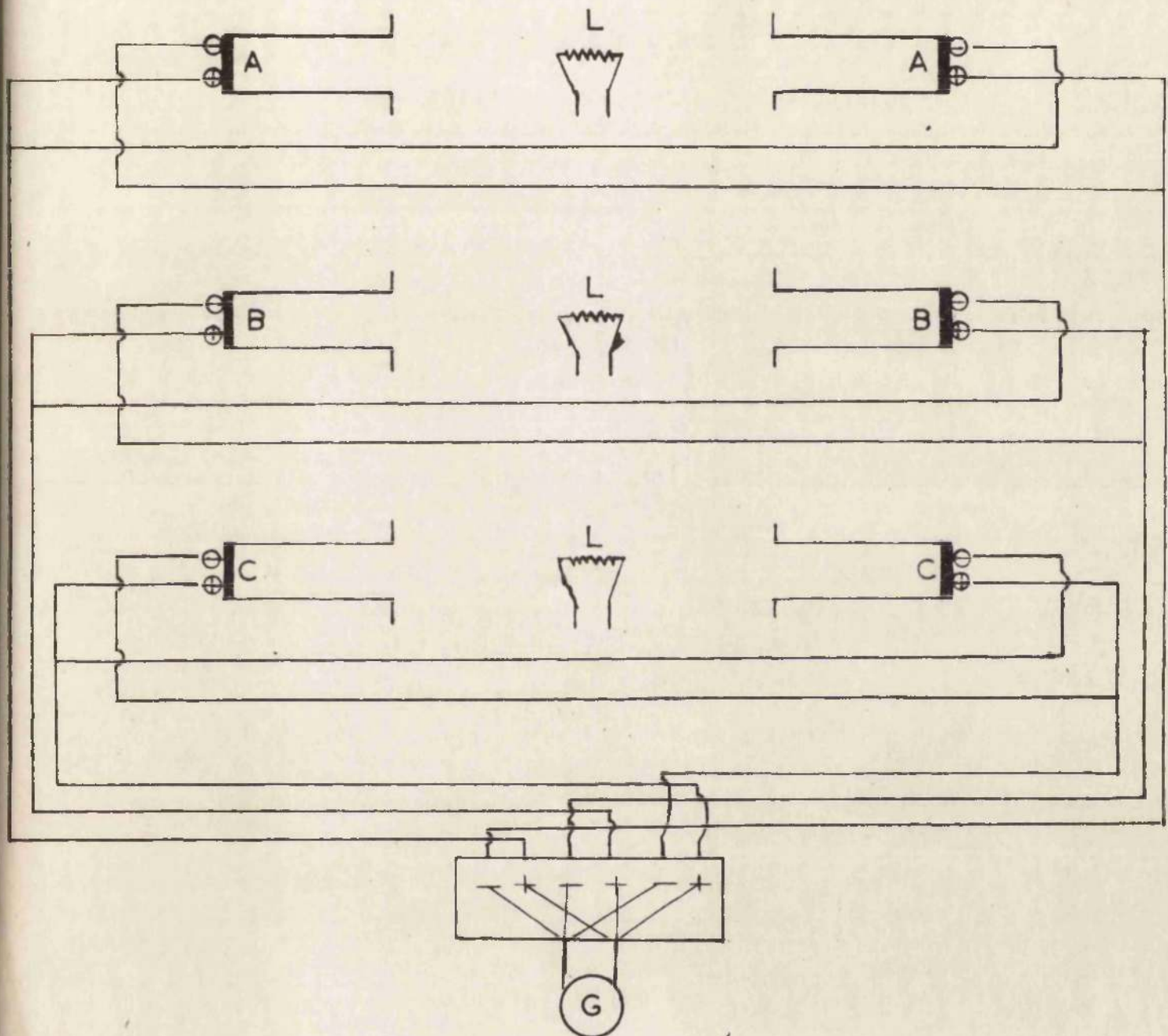


FIG. No. 5

PHOTOELECTRIC CELL CIRCUIT DIAGRAM



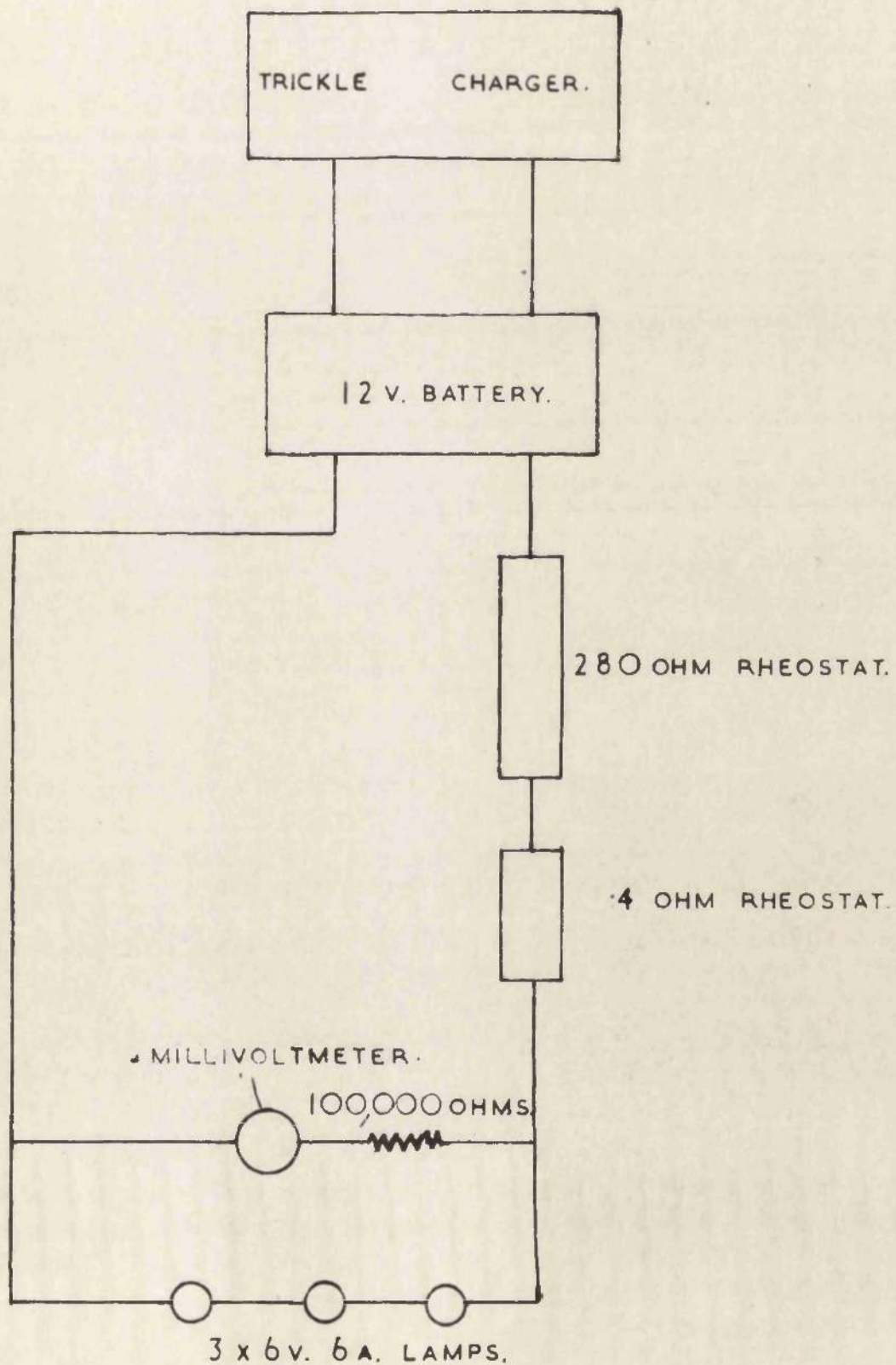
- A — PHOTOELECTRIC CELLS, TOP SYSTEM.
- B — " " " MIDDLE " "
- C — " " " BOTTOM " "
- L — 6 V. 6 A. LAMPS.
- G — MIRROR GALVANOMETER.

bore, through which the electrical cable and condenser tubing is led and attached to the T.P. head. When not in use the T.P. head is withdrawn into the compartment (B) which is bolted to the top of the chamber over a rectangular opening. The compartment is fitted with a sliding door which is closed onto the rubber gasket, when the T.P. is in the chamber. When the T.P. is withdrawn from the chamber the compartment is sealed off from the chamber by a sheet of blackened aluminium held against the chamber top by the rubber gasket. To prevent escape of the dust to the atmosphere a rubber seal is attached to the roof of the T.P. compartment and the rubber tubing passed through the seal which is made from a piece of 1/8 in. rubber sheet with a 3/4 in. hole. The remainder of the T.P. unit is standard equipment and is operated in the manner recommended by Casella(55).

Voltage Supply and Lamp Circuit.

To obtain accurate results from the above apparatus it is necessary to provide a stabilised voltage supply. The circuit diagram for this purpose is shown in Fig. 6. The power for the three lamps is supplied from a 12V accumulator which is constantly charged by a trickle charger. A voltmeter is connected across the lamps so that the voltage supply to the lamps can be checked and adjusted by means of two rheostats arranged in series with the lamps. By altering the voltage across the lamps the intensity of the light source can be controlled and the output from the photoelectric cells

FIG. No. 6
CIRCUIT FOR PRODUCING
STEADY VOLTAGE



altered.

Apparatus for the Production of a Fine Dust Cloud.

Massie(41) prepared dust samples of known sharply graded size below a maximum of 10 microns for his sedimentation work. This method consisted in suspending ground sand in water containing 0.05% "Dispersol" wetting agent and obtaining the desired size fraction by careful sedimentation. The procedure, although successful, was laborious and time consuming.

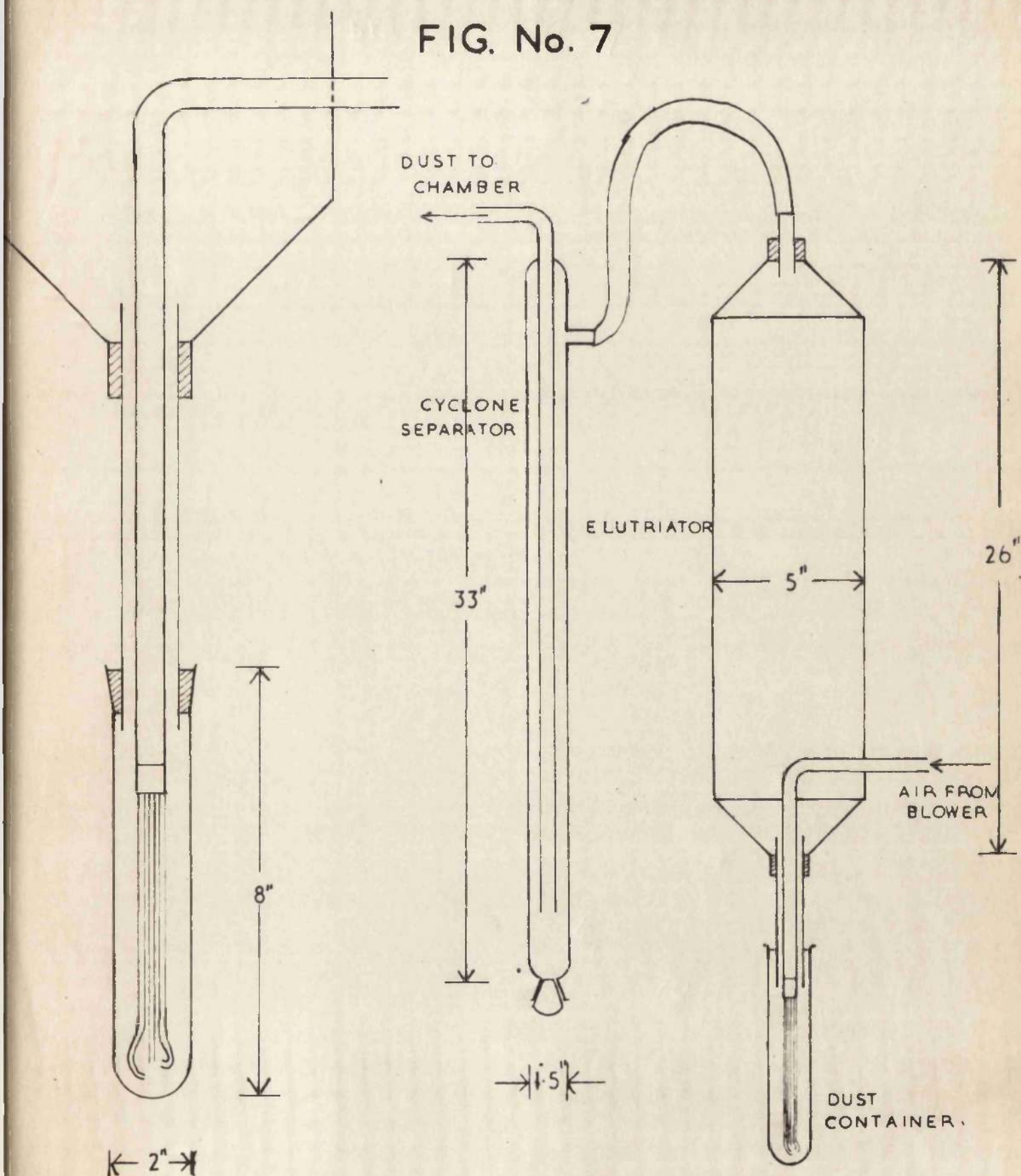
For the work envisaged with the new dust chamber this method of preparing a dust sample had two disadvantages:-

1. The quantity of dust required for the large chamber rendered the liquid sedimentation impracticable.
2. Since the object of the work was the investigation of the wetting of silica dust with aqueous sprays, it was considered inadvisable to have the dust particles in contact with water and a S/A agent previous to suspending it in air.

The apparatus employed with the chamber just described is a modified form of that used by Dautrebande et al.(56) and is shown in Fig. 7. Low pressure air is supplied by an air blower to the dust container in the apparatus. The air enters the dust container through three small bore copper tubes, creating a vortex which lifts the dust up through the elutriator chamber, through the cyclone separator and into the dust chamber. Using this method only the very small particles reach the dust chamber and give a dust cloud which will remain in suspension over a sufficiently long time to

APPARATUS FOR GENERATING DUST CLOUD

FIG. No. 7



enable measurements to be made. The concentration of dust in the chamber can be varied by altering the duration of blowing.

The ability to reproduce dust concentrations with this apparatus allowed spray efficiencies to be compared at similar concentrations of dust. The size range of dust obtained at the end of one hour's sedimenting was also found to be approximately reproducible and was in the range 0.4 micron (limit of resolution of the Vicker Projection Microscope) and 6 microns. This range of particle size was considered suitable since the size range 0.2 to 10 microns is believed to be the most dangerous and the most difficult to remove from suspension in air.

The dust used to generate the cloud was MSC silica dust, a commercial grade of ground silica from Goed Talon, North Wales (supplier, Colin Stewart, Winsford, Cheshire) which had the following composition:-

SiO ₂ (quartz)	92.35%
Fe ₂ O ₃ + Al ₂ O ₃	7.65%

The density of the ground silica was 2.61 gs/cc. and the particle size was 95% by weight < 5 microns. The MSC dust was dried at 120°C for 24 hours and kept in a desiccator until it was required. The size range of the dust cloud produced by the apparatus is shown in Table 7 compared with the size range of dust present in a bituminous coal mine.

Operation of Apparatus.

The voltage across the three lamps was adjusted to six volts

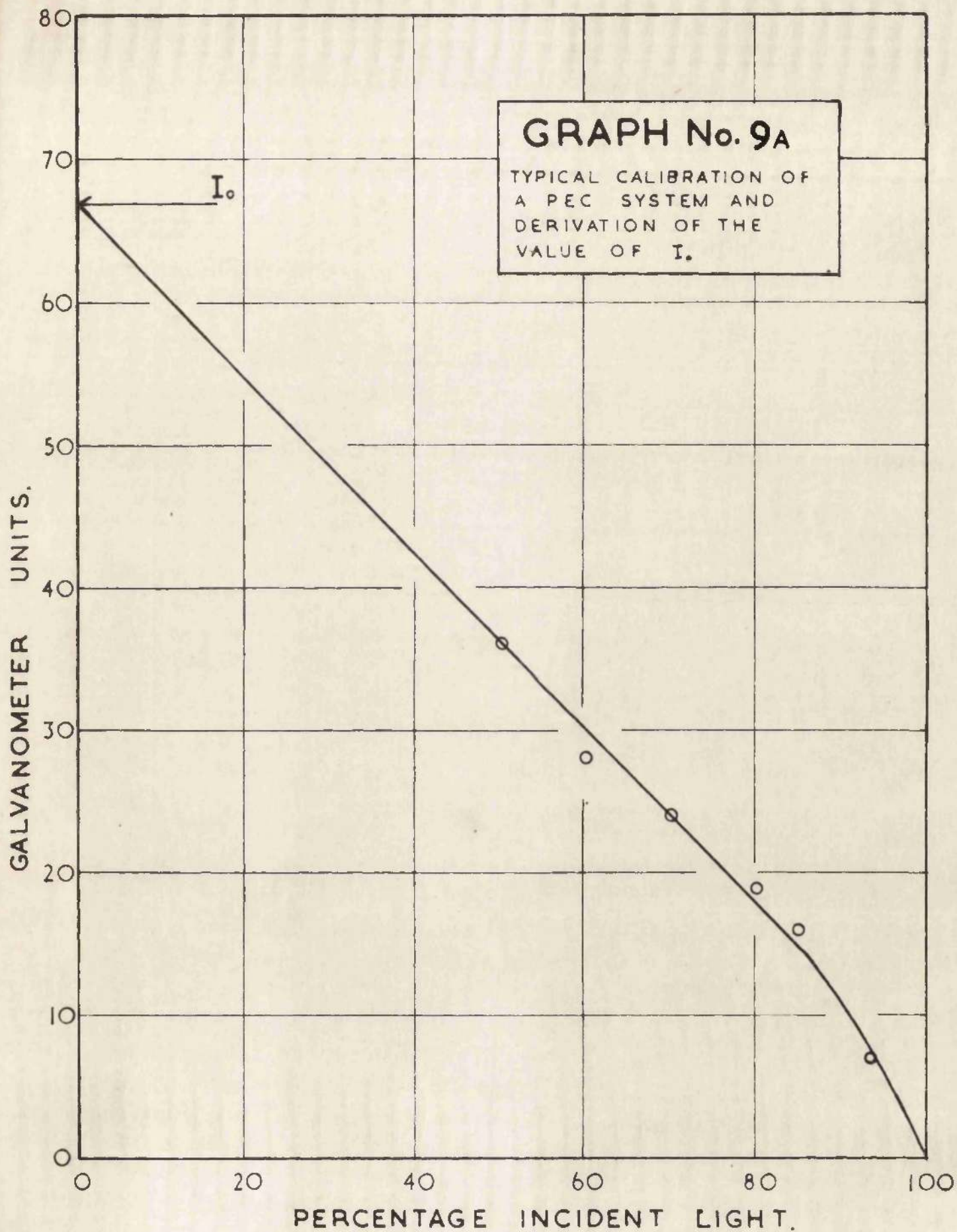
Table No.7

Comparison of Dust Cloud formed by Apparatus with that in a
Coal Mine.

Dust Cloud Prepared by Apparatus		Dust in Bituminous Coal Mine. (17)	
Size in Microns	Percentage Number	Size in Microns	Percentage Number.
0.4 - 0.8	25.2	0.5 or less	c.65
0.8 - 1.6	58.2	0.5 - 1	30
1.6 - 2.4	12.9	1 - 2	4 - 9
2.4 - 3.2	2.8	<2	remainder
3.2 - 4.0	0.9		

by means of two rheostats, for coarse and fine adjustment respectively. The photoelectric cell systems were left for two hours to settle down and the zero drift measured during this time. After the two hours the first pair of photoelectric cells was linked to the galvanometer, and adjusting the amount of light reaching the cell on the near side of the chamber by means of a strip of blackened foil, the cells were balanced against each other to give a zero reading on the galvanometer.

The photoelectric cells were calibrated with Ilford gelatine neutral density filters ranging from 25% to 85% transmission. A piece of optically flat glass was used to give a further point at 94% transmission. This enabled a graph of galvanometer deflection against light transmission to be drawn and showed if a linear response was being obtained. Extension of the straight line section of this graph (see Graph 9) to zero transmission gave the deflection for the light passing through the chamber with zero interference. After calibrating the photocells in this way the slides on the chamber were closed to prevent dust reaching the lenses and cells and also to prevent it escaping to the atmosphere. The fan was switched on and allowed to run for 15 seconds before the dust was blown in. The dust was blown in for the required time interval, (i.e. from 15 seconds to one minute), the fan running all the time. The fan was allowed to run for a further 15 seconds after the dust generator was switched off. The slides were withdrawn to allow the light to



traverse the dust cloud and galvanometer readings taken at 10 minute intervals over the period of sedimentation. A graph of these readings against time gave the sedimentation curve for the dust (Graph 10).

When a test was being carried out to study the effect of a spray, the procedure was the same up to 55 minutes after charging the chamber with dust. At this time a further reading was taken and the slides were closed. The spray was added at the end of one hour. After the spraying was completed the slides were again opened and readings taken on the galvanometer over a further period of one hour when the procedure for spraying could be repeated.

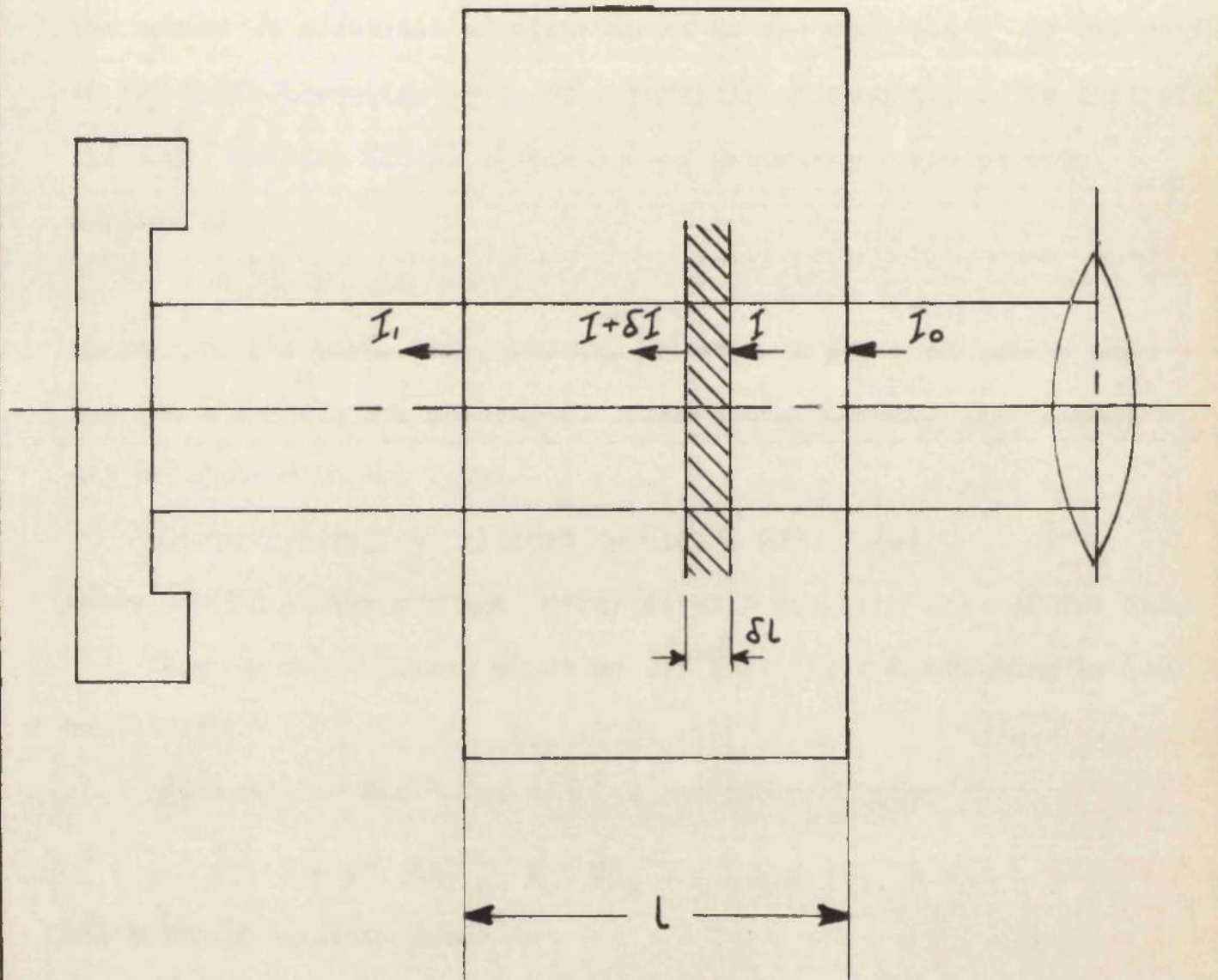
Comparison of the plot of actual galvanometer deflection against time, or percentage galvanometer deflection against time for sedimentation alone, and again for sedimentation and spraying, showed the effect of a spray on the concentration of an airborne dust. Application of a form of the Beer-Lambert Law, as described in the next section, to the results obtained before and after spraying, gave the percentage reduction in the surface area of the dust cloud.

Theoretical

Consider Fig. 8 in which is shown a vessel length L measured in the direction of the light beam containing a suspension of powder of concentration C gs/cc . Across the cell is projected a beam of light, of cross section A square units, having an incident energy of I_0 units. Within the cell is an element of suspension of length dL measured in the direction of the light beam. Now the

FIG. No.8

LIGHT EXTINCTION SYSTEM.



following relationships apply.

Light energy falling on the element = IA (1) and similarly light energy leaving the element

$$= I(\Delta - \text{effective projected area of the particles in the beam})$$

$$= I(\Delta - k \sum_0^d K_x N d_x^2) \quad (2)$$

where k depends on the shape and orientation of the particles, N is the number of particles of diameter dx in the beam and K_x is the ratio of the light-obscuring power of a particle of diameter dx to that for the same particle if the square law of geometrical optics were applicable.

$$N = \Delta dL \quad Cn \quad (3)$$

where n is the number of particles of size dx per g of powder and the other symbols are as before. The energy leaving the element may be written in the form:-

$$\text{Energy leaving the element} = \Delta(I + dI) \quad (4)$$

where $I + dI$ is the average energy density over the area of the beam.

Then on substituting equation (3) into (2) and equating to (4) we obtain.

$$\Delta(I + dI) = I(\Delta - kCA \, dL \sum_0^d K_x n d_x^2) \quad (5)$$

$$\text{or} \quad \frac{dI}{I} = -kC \, dL \sum_0^d K_x n d_x^2$$

which on integration leads to

$$\log_e I_0/I_1 = kCL \sum_0^d K_x n d_x^2 \quad (6)$$

Consideration of the derivation of these equations will show that the following assumptions are made:-

- (1) The particles are absolutely opaque.
- (2) There is no reflection between the particles and the walls

of the vessel.

(3) Any deviation in the light-obscuring power of a small particle from that given by the "square law" is covered by the factor K_x , which should thus depend upon the particle size, wavelength of light, refractive index of particle and fluid, etc; but not upon the physical size of the apparatus.

(4) The concentration of the suspension is such that no two particles, within the element of suspension dL thick, fall on the same line parallel to the light beam.

From the last condition, which must be true as $dL \rightarrow 0$, the integration of equation (5) is valid for all values of concentration.

The light extinction method can be used to compare the concentration of the dust cloud before spraying with the concentration after spraying. If I_0 is the intensity of the light beam in the absence of absorption by particles and I_B and I_A , the transmitted intensities before spraying and after spraying respectively, then the ratio of the projected area of the particles present in the beam after spraying to the projected area of the particles present before spraying is given by the expression:-

$$\frac{\log_e \frac{I_0/I_A}{\log_e \frac{I_0/I_B}}}{\log_e \frac{I_0/I_B}} \text{ ----- (7)}$$

This expression for the ratio of the projected area also represents the ratio of the surface area of the dust, since the mean projected area of a particle of any shape in turbulent suspension is equal to one quarter of the geometric surface of the particle (57). The expression

is subject to an error since it assumes that the value for K_x is the same before and after spraying. A number of investigators have shown that for particles from 0 to 5 microns the value for K_x varies greatly with the particle size. (50,58,59). Subsequent investigations, with the T.P. as described in Section 5 of this thesis, showed that a change in size distribution did result due to spraying but the change was not very great for a period of spraying of two minutes and the error due to the change was considered negligible compared with the error in the apparatus.

Other sources of error in light extinction apparatus have been exhaustively investigated by Rose et al. Rose and Lloyd (60) showed that many of the sources of error encountered are eliminated when the light sensitive receiver subtends a very small angle at the centre of the suspension. Rose also showed that provided $\log_{10} I_0/I$, does not exceed 0.5, i.e., for more dilute suspensions the error in the estimation of the projected area with apparatus, of similar design to that used in this work, was 5%.

The solid angle subtended by the photoelectric cells was 0.0029 solid radians compared with a solid angle of 0.0115 solid radians used by Rose, which was found to give satisfactory results up to a value of 0.5 for $\log_{10} I_0/I$.

The light extinction method of measuring concentration has its limitations and should be emphasized at this point.

(1) The method is strictly applicable to particles whose dimensions are large compared with the wave length of light. It is

generally agreed that the presence of smaller particles is underestimated because of the practical impossibility of eliminating all forward scattered light. The total area of the particles is thus itself underestimated.

(2) The method is one which measures particle areas. It should be stressed that the expansion of the result involves additional assumptions which are questionable.

Specimen Calculation of Percentage Reduction in Surface Area.

The intensity of the light beam is proportional to the galvanometer deflection since calibration of the apparatus shows a linear relationship between light intensity and galvanometer deflection over the range where the galvanometer readings are taken in the estimation of the dust concentration.

I_0 = Intensity of the light beam in the absence of absorption by particles 64.8 cms.

IB = Transmitted intensity after 55 minutes sedimentation and before spray is added = 65.3 cms.

IA = Transmitted intensity after spray has been added.

$$\text{Ratio. } \frac{\log_e I_0/IA}{\log_e I_0/IB} = \frac{\log_{10} I_0/IA}{\log_{10} I_0/IB} = \frac{\text{surface area of dust cloud before spray}}{\text{surface area of dust cloud after spray.}}$$

The figures above are for the spray run when water is sprayed downward through the dust cloud for two minutes.

Water Pressure 62 lb./in.²

The results are for the top system of photoelectric cells.

$$\frac{\log_{10} I_0/IA}{\log_{10} I_0/IB} = \frac{\log(64.8/61.2)}{\log(64.8/56.3)} = \frac{\log 1.058}{\log 1.151} = \frac{.0244}{.0611}$$

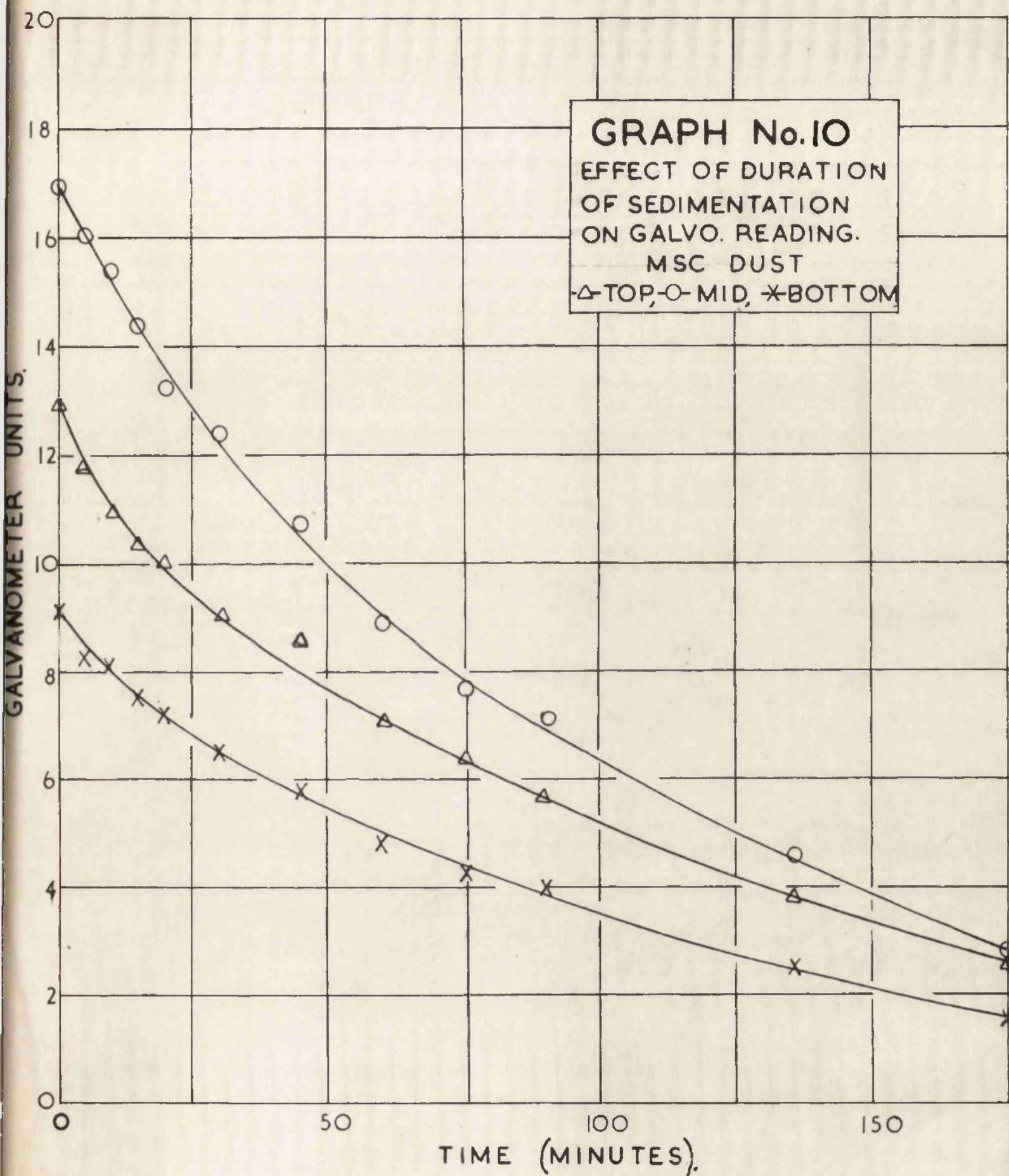
.. Amount removed by spray	= 1-.40
	= .60
.. Percentage reduction in surface area	= <u>60</u>

Analysis of Results.Graphs 10 to 20

The effect of different dust concentrations on the form of the sedimentation curve and the variation of concentration at different depths in the chamber was investigated and the results shown in Graphs 11 to 14. The sedimentation curve was constructed by plotting percentage galvanometer readings against time. The initial reading taken on the galvanometer five minutes after the dust had been blown into the chamber was taken as representing 100%.

The chamber was charged with MSC dust by blowing for different lengths of time, i.e. 15, 30, 45, and 60 seconds, to find the range of dust concentration which could be obtained and also to show the effect of concentration on the shape of the sedimentation curve. The three different photoelectric cell systems gave different original deflections on the galvanometer owing to differences in the characteristics of the cells the lamp bulbs and the housings for the systems. This is shown in Graph 10.

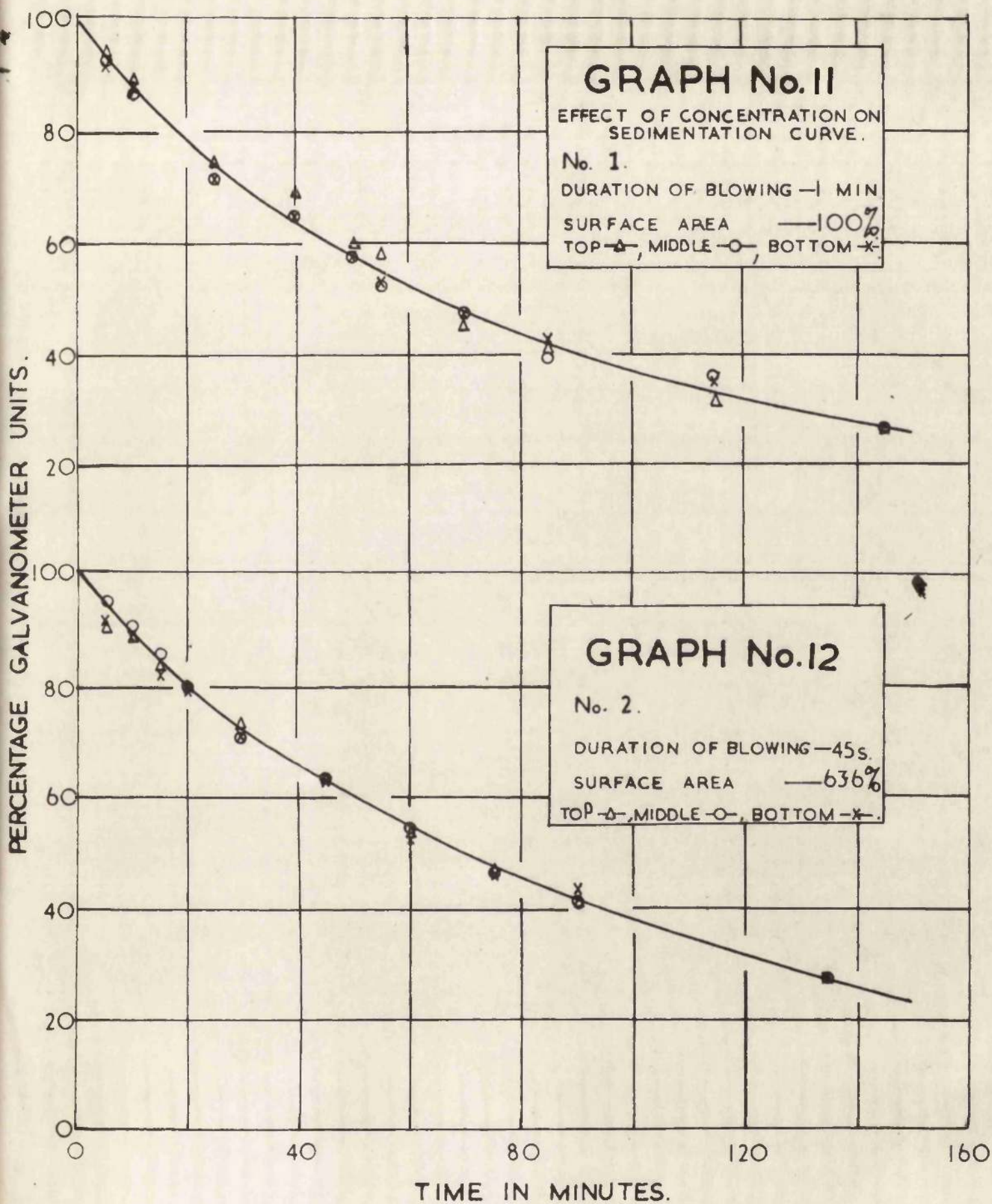
The galvanometer deflections were converted to a percentage reading and plotted against time to give the sedimentation curves shown in Graphs 11 to 14. It was found that the percentage galvanometer readings coincided for the three systems of photoelectric cells showing that the variation of concentration with time was uniform throughout the chamber. Comparison of the sedimentation curves for four different initial concentrations of dust (four different durations



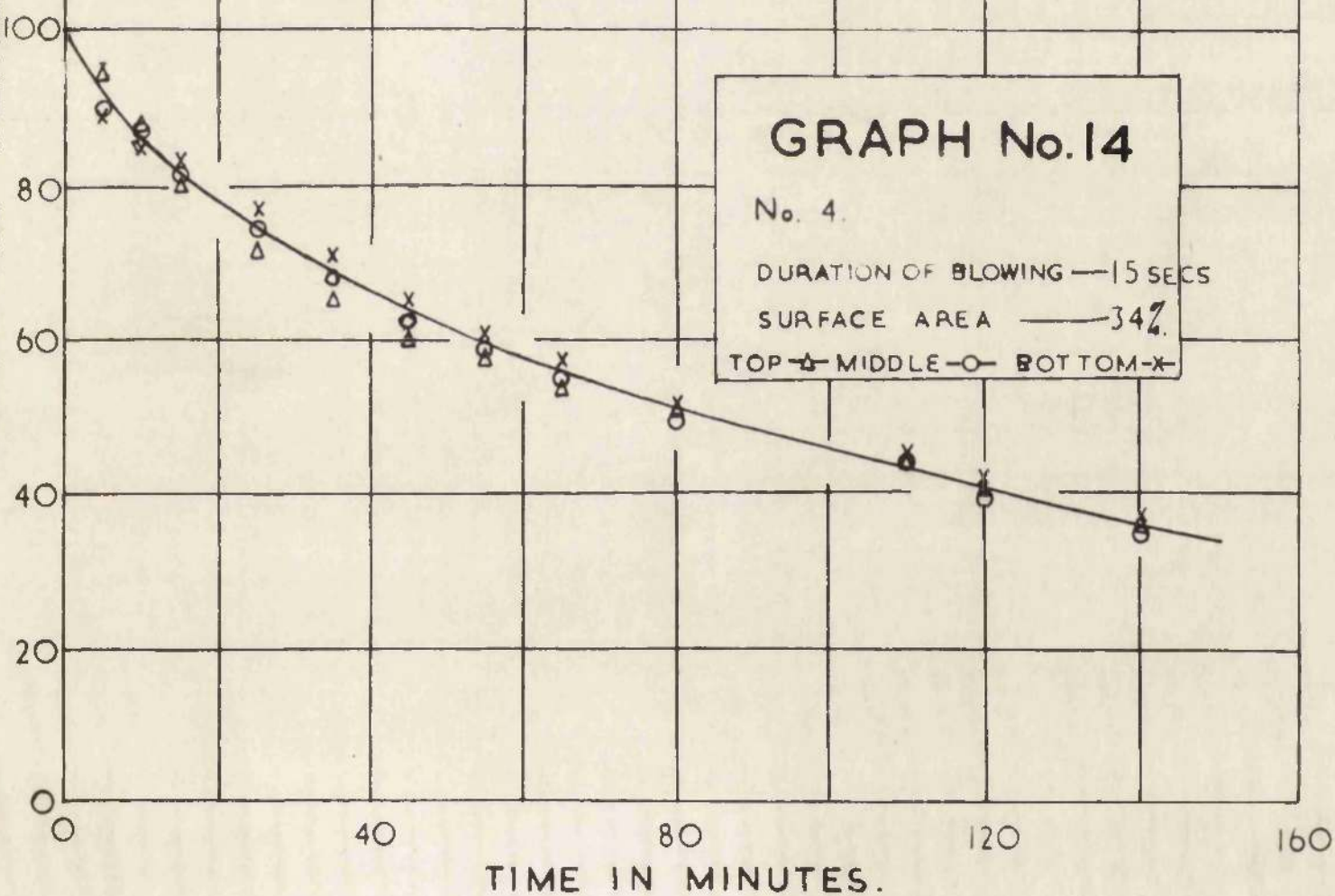
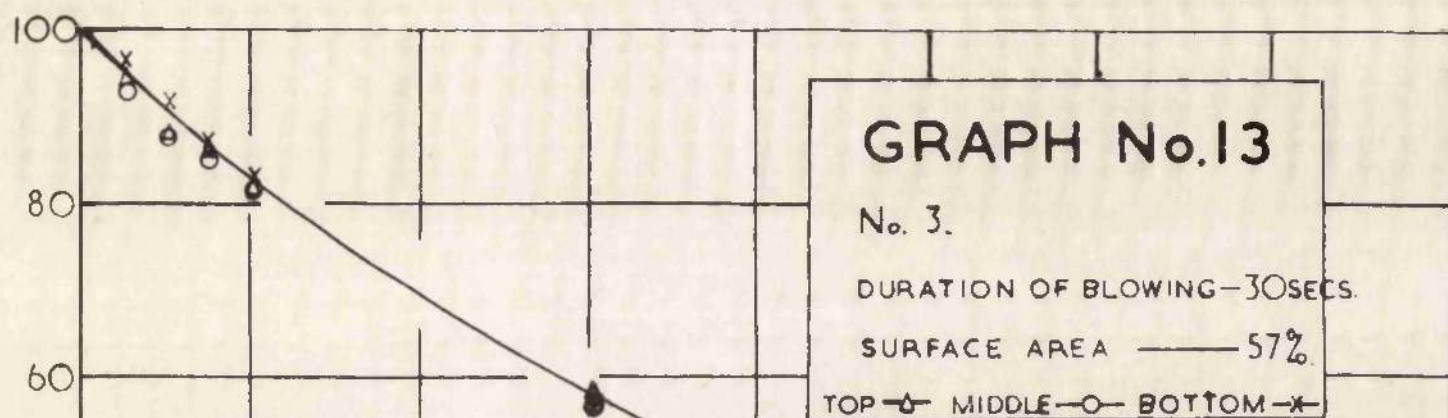
of charging) showed that the curves for the three highest concentrations of dust were almost identical. This proved that over the range of concentration covered by the curves the rate of sedimentation was the same. The range of dust concentration covered by these three curves was not great, however. If one expressed the surface area of dust produced by blowing for one minute as 100% then by blowing for 45 and 30 seconds the surface areas of the dust cloud were 63.6% and 57%. The curve obtained by blowing for 15 seconds which gave a dust cloud with a surface area 34% of that obtained by blowing for one minute showed a slower decrease in concentration with time. This suggested that aggregation was not so pronounced at this concentration as it was at the three higher concentrations. From the values given for the surface areas of the dust cloud it can be seen that by altering the duration of blowing from 15 seconds to one minute the concentration of the dust can be increased threefold.

Effect of Spraying.

The amount of dust removed by spraying was represented in two ways. The graphs of percentage galvanometer readings against time were constructed for the spraying run and a plot of the type shown by Graph 16 obtained. The vertical section of the plot represents the reduction in galvanometer reading due to spraying. Comparison of the curves obtained (Graphs 16 to 20) shows the increase in removal with duration of spraying. The vertical section of the plot can be converted to represent the percentage reduction in surface area of the



PERCENTAGE GALVANOMETER UNITS.



dust in the chamber by application of the form of the Beer-Lambert law described above.

The Effect of Duration of Spraying on Dust Concentration.

Tests were carried out to determine the variation of the amount of dust suppressed by spraying for different lengths of time. The chamber was charged and the dust allowed to sediment for one hour. Spraying was carried out for 30 seconds, 1 minute, 2 minutes, 5 minutes, and 10 minutes. The results obtained for percentage galvanometer reading against time are shown in Graphs 16 to 20. The reduction in surface area was calculated for the three photoelectric cell systems and the results are shown in Table 8. The values for each photoelectric cell system is shown as well as average values for the three systems. Comparison of the results for the top, middle and bottom systems of cells shows that there is no preferential removal from any section of the chamber.

It was originally thought that it would be possible to distinguish preferential removal of dust particles in the section of the chamber nearest the spray nozzle, where the spray droplets have the highest velocity. This effect, if it occurred, was masked by the turbulence in the chamber and thorough mixing of the dust cloud by injection of the spray.

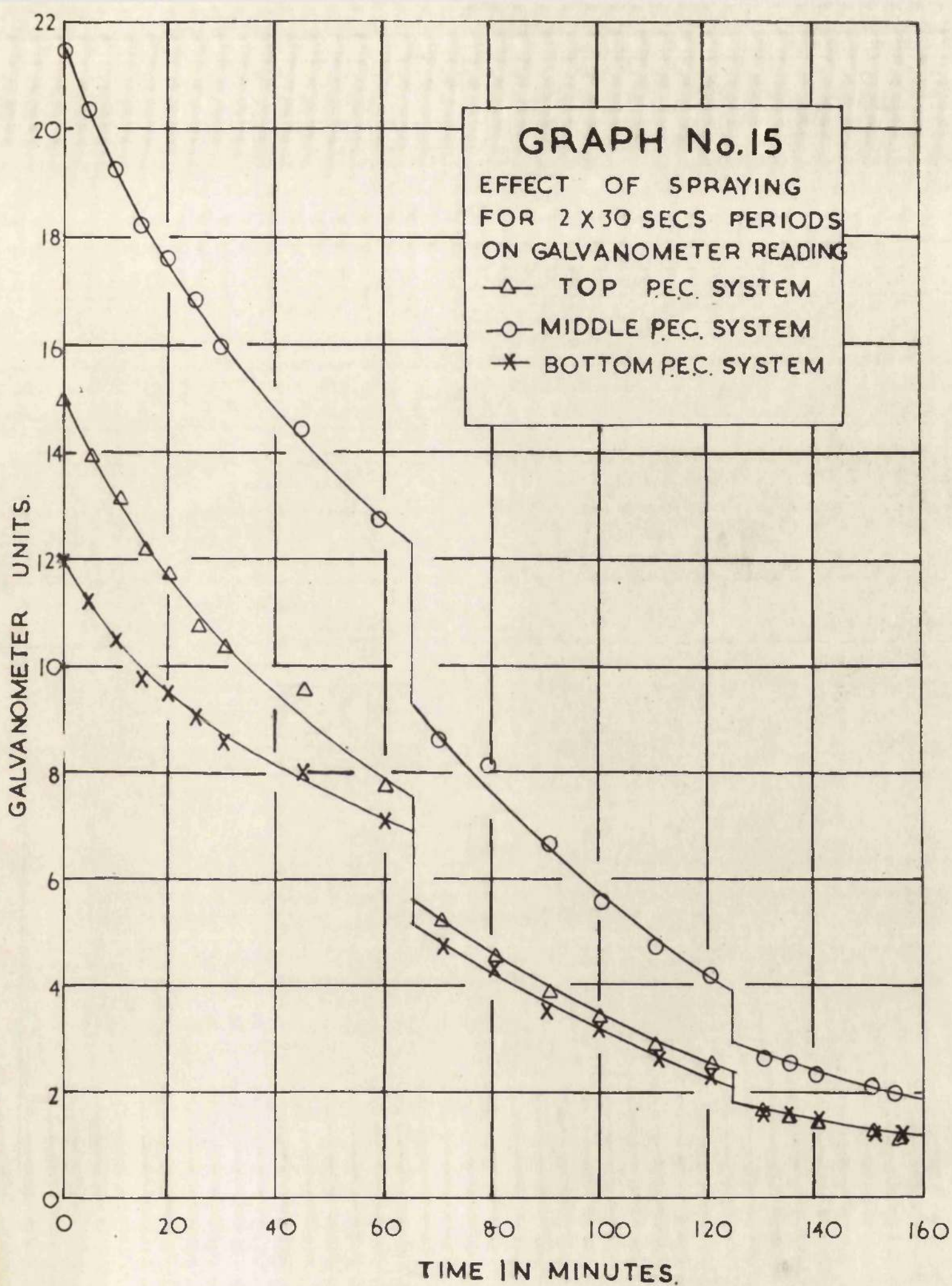
The average values for the percentage reduction in surface area of the airborne dust are plotted against duration of spraying and Graph 26 obtained. The graph rises steeply up to two minutes spraying when it gradually flattens out to give a slower rate of dust removal. The decrease in the rate can be explained by the fact that the dust concentration decreases as spraying proceeds and thus the chance of

Table No. 8.

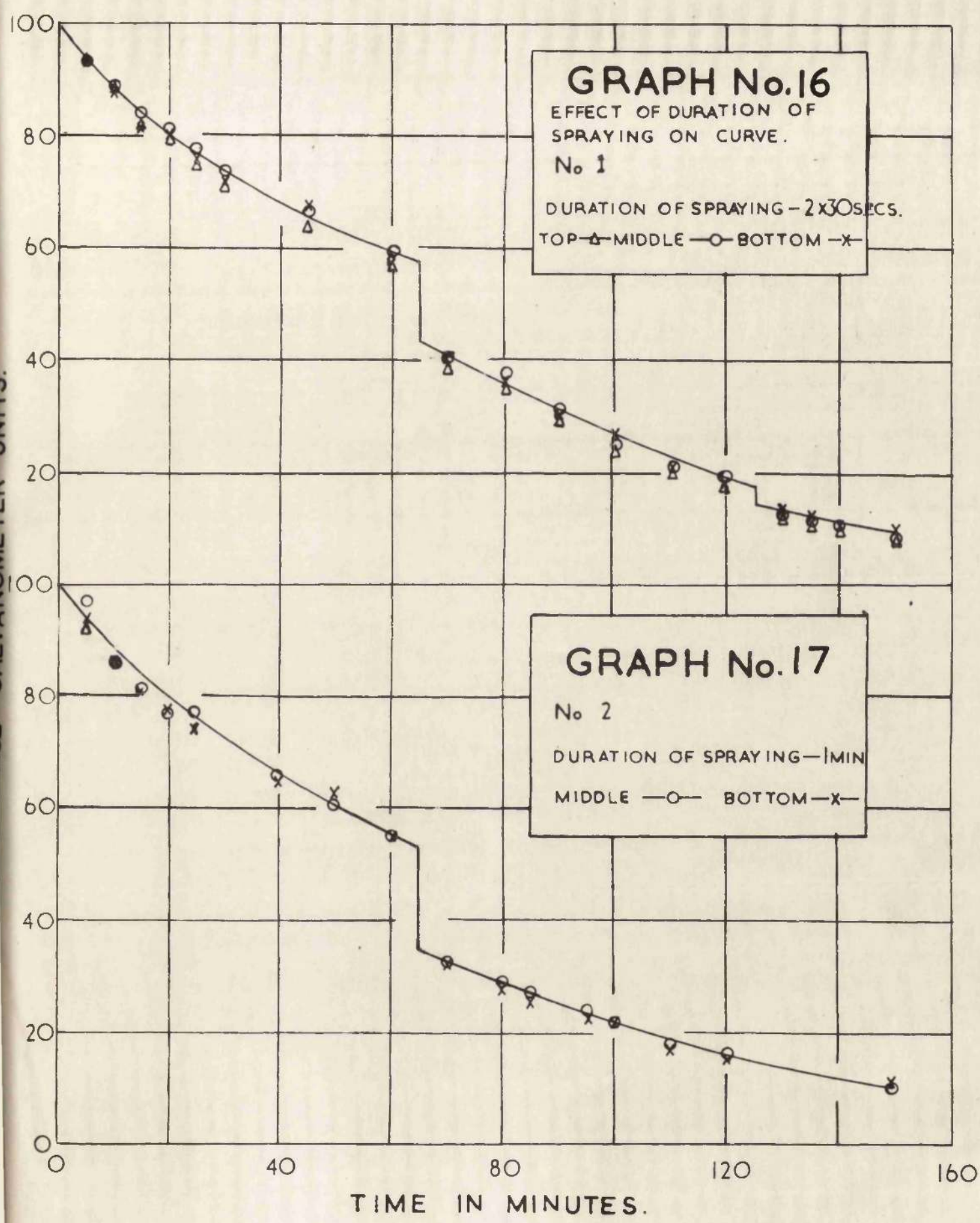
Effect of Duration of Spraying on Dust Cloud.

Spray Nozzle No. 1, Water Pressure 62 lb./in.².

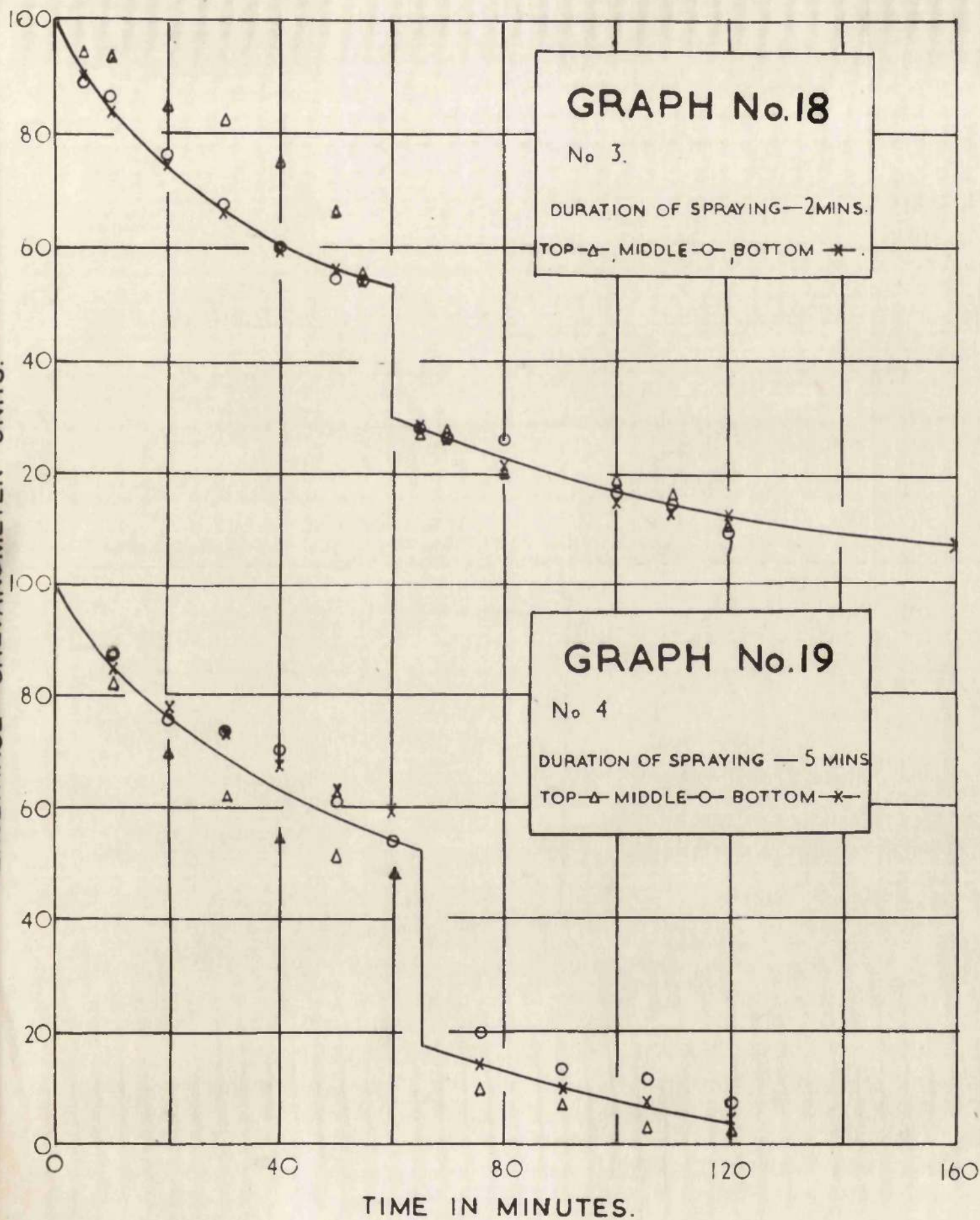
Duration of Spraying	Percentage Dust Removal			Average
	Top	Middle	Bottom	
30 secs	27.0	24.5	24.5	25.3
1 min	45.0	43.0	35.0	41.0
2 mins	59.0	67.0	59.0	61.0
5 mins	68.0	83.5	66.5	79.0
10 mins	94.0	98.5	98.0	97.0

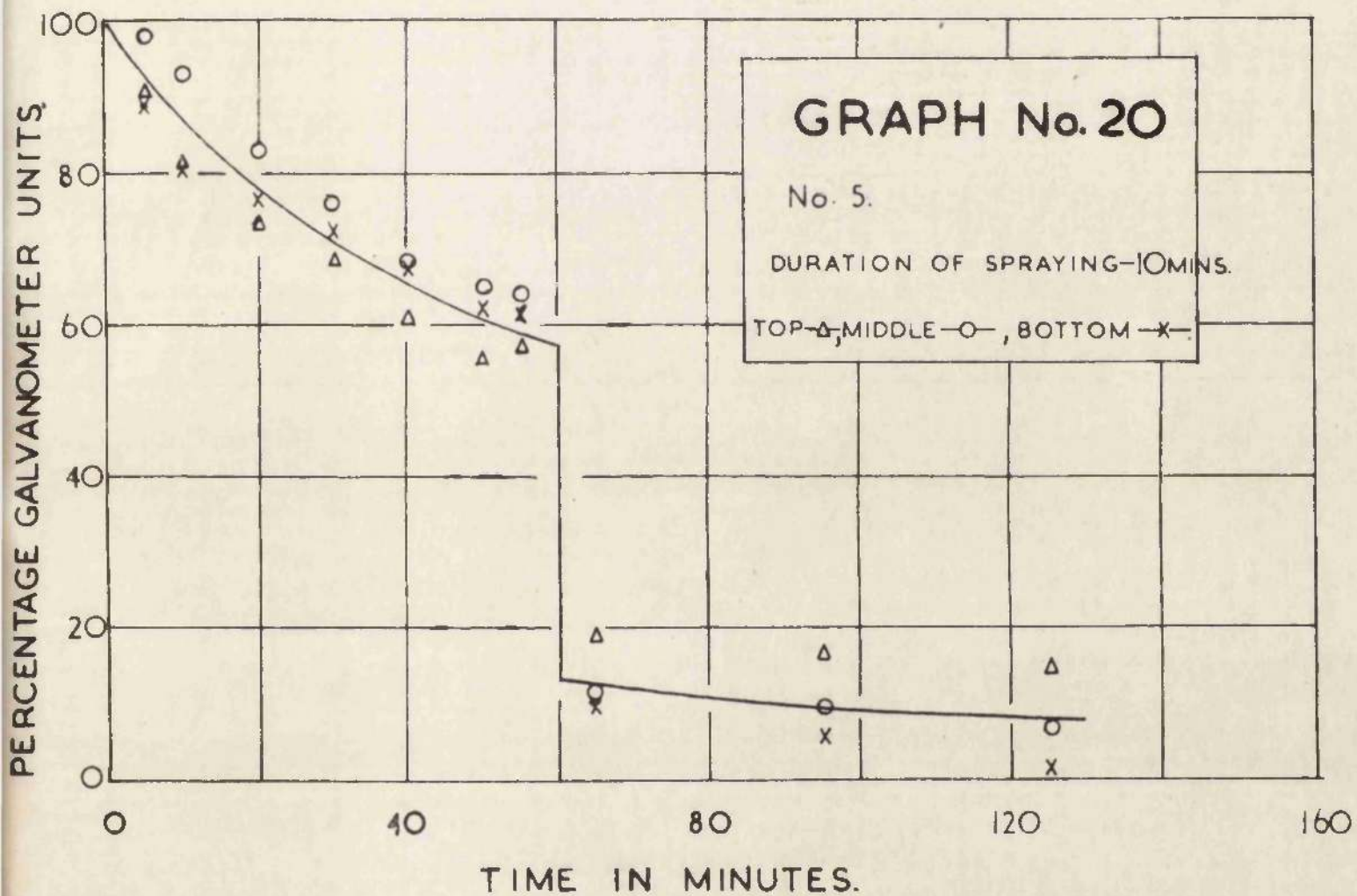


PERCENTAGE OF METAL REMOVED



PERCENTAGE GALVANOMETER UNITS.





the water droplets striking the particles will also decrease. If this were the only factor affecting the removal of the dust the curve would be expected to conform to an exponential equation. This is not so, as can be seen in Graph 26 since the exponential equation which satisfies the values for 30 seconds, 1 minute, and 2 minutes does not satisfy the values for 5 minutes and 10 minutes. An additional factor which would contribute to the faster rate of dust removal up to two minutes spraying would be the "knockdown" of the larger dust particles by spray droplets. This would result in a greater reduction in projected area than would have occurred if a smaller particle had been removed.

Thus the shape of the curve of percentage reduction in surface area against time is governed by the concentration of the dust and the size of the dust particle.

The Effect of Spraying at Different Times.

Two spraying tests were carried out. In the first, the dust was sprayed for one minute after sedimenting for one hour; in the second, the dust was sprayed for 30 seconds at the end of one hour and 30 seconds at the end of two hours. From the graphs of percentage galvanometer readings against time for the two tests (Graphs 16 and 17) it can be seen that the concentration at the end of two hours was the same.

In this case the factors affecting the removal of the dust have acted against each other. It would be expected that spraying at the higher concentration would be most effective but this is cancelled

out by the decrease in the rate of sedimentation due to the lower concentration remaining after spraying for one minute.

The Effect of Altering the Direction of Spraying.

The view has been expressed by Terrel (61) that very small dust particles, too small to be efficiently wetted by spray droplets, are brought down by a sweeping action caused by the passage of the drops.

To demonstrate the extent of this effect the amount of dust removed by spraying both downwards and upwards through the dust cloud was investigated and the results obtained are presented in Table 9.

These results show that no advantage is derived by altering the direction of spraying. Some of the droplets formed by spraying upwards will pass through the dust cloud twice -- once upwards, during spraying, and once downwards under the influence of gravity. Any advantage which is derived by the droplets passing through the dust cloud twice will be cancelled out, since the force of gravity decreases the velocity of the droplets while they are rising upwards, the result being the same efficiency of dust removal as is obtained by spraying downwards.

Effect of S/A Agents.

In the investigation of the effect of S/A agents on the efficiency of suppression of airborne silica dust by spraying, two S/A agents were used.

(1) Lissapol NDB is a dilution of Lissapol N in water. This S/A agent is non-ionic in aqueous solution and is an ethylene oxide condensate. It is classified as a detergent and wetting agent

Table No. 9.

Effect of Altering the Direction of Spraying.

Spray Nozzle No. 1, Water Pressure 62 lb./in.².

Direction of Spraying	Solution	Duration of Spraying	Reduction in Surface Area
Upward	water	2 mins	61%
Downward	water	2 mins	62%

and is recommended by I.C.I. Ltd. for dust suppression.

(2) Alcopol O is dioctyl sulpho succinate and for the work on the light extinction method for dust estimation, a solution of the S/A agent in alcohol and water was used. This S/A agent is anionic in solution and is classified as a detergent and wetting agent.

0.5% solutions of Lissapol NDB and Alcopol O were made up in water and spraying runs carried out in the usual way, the spray being added for two minutes after the dust had been allowed to sediment for one hour. The reduction in the surface area of the airborne dust by spraying was calculated for water, Lissapol NDB, and Alcopol O. The results are presented in Table 10 and show that at a water pressure of 62 lb./in.² and a period of spraying of two minutes there was no increase in the efficiency of dust suppression using a 0.5% Lissapol NDB solution instead of water alone and a 0.5% solution of Alcopol O resulted in a decrease in efficiency of suppression.

Effect of the Concentration of a S/A Agent.

To show the effect of altering the surface tension of the water used to form the spray, solutions of different concentrations of Lissapol NDB were prepared and used. The concentrations chosen were 0.015%, 0.1%, 0.5% and 2% by weight. The reason for selecting these concentrations can be seen from Graph 5, the graph of surface tension against concentration of Lissapol NDB. 0.015% solution of Lissapol NDB in water corresponds to a surface tension intermediate between that of water alone and the minimum surface tension obtainable for an aqueous solution of Lissapol NDB. 0.1% corresponds

to the minimum concentration of the flat section of the graph of surface tension against concentration. The 0.5% and 2.0% solutions of Lissapol NDB give the minimum surface tension for an aqueous solution of Lissapol NDB with the S/A agent present in excess.

The results obtained using these concentrations of S/A agent are shown in Table 11 compared with the percentage reduction in surface area of the dust using water alone. The results show that no alteration of the efficiency of suppression of the dust is brought about by using Lissapol NDB (0.015%, 0.1%, 0.5%, 2.0%) when the pressure of the solution in the spray vessel is 62lb/in². The explanation of this will be dealt with later in this work (Section 4).

Table No. 10.

Effect of S/A Agents on Dust Suppression.

Spray Nozzle No. 1, Water Pressure 62 lb./in.².

S/A Agent	Concentration	Surface Tension	Duration of Spraying	Reduction in Surface Area
Water alone	--	72.0 dynes/cm	2 mins	61%
Lissapol NDB	0.5%	29.5 dynes/cm	2 mins	61%
Alcopol O	0.5%	28.0 dynes/cm	2 mins	52%

Table No. 11.

Effect of Altering Concentration of S/A Agent.

Spray Nozzle No. 1, Water Pressure 62 lb./in.².

S/A Agent	Concentration	Surface Tension	Duration of Spraying	Reduction in Surface Area
Water alone	--	72.0 dynes/cm	2 mins	61%
Lissapol NDB	0.015%	55.0 dynes/cm	2 mins	58%
Lissapol NDB	0.1%	31.0 dynes/cm	2 mins	57%
Lissapol NDB	0.5%	29.5 dynes/cm	2 mins	61%
Lissapol NDB	2.0%	29.0 dynes/cm	2 mins	63%

Conclusions.

An apparatus has been developed which is suitable for the examination of the sedimentation of dust and the investigation of the effect of sprays on the dust.

From experiments with the apparatus it is possible to obtain two items of information.

(1) The rate of sedimentation of the dust cloud and the reduction due to spraying, by plotting percentage galvanometer readings against time. This method enables results to be obtained on a comparative basis only, but it is useful in obtaining quick results.

(2) The reduction in surface area of a dust cloud due to spraying, by application of a form of the Beer-Lambert Law. The results obtained by this method have a physical significance but still do not give any information on the size range of dust suppressed. They therefore do not show the effect of the spray on the dust cloud from a health hazard point of view.

From the work completed the following information has been obtained:-

(1) The rate of sedimentation of the lower concentration of dust is less than the other three higher concentrations, suggesting the effect of aggregation at the higher concentrations.

(2) The direction of spraying of the dust cloud does not affect the amount of dust suppressed.

(3) The plot of the reduction of dust concentration with duration of spraying does not conform to an exponential equation,

as would be expected if the only factor influencing the removal of the dust was the concentration. It is suggested that the initial periods of spraying resulted in the removal of the larger dust particles with a proportionally large reduction in surface area of the cloud.

(4) The use of S/A agents in the sprays did not result in an improvement in spray efficiency. A 0.5% solution of Lissapol NDB was as effective as pure water in suppressing the dust, while a 0.5% solution of Alcopol O in alcohol was less effective than water and Lissapol NDB.

(5) Varying the concentration of Lissapol NDB in the spray solution did not affect the efficiency of dust removal.

SECTION 3.

Description of the Properties of Aerosols.

The properties of aerosols differ in several important respects from these of disperse systems in liquids and solids. Firstly, owing to the relatively small viscosity and specific gravity of gases, the liquid or solid particles of the disperse phase tend to settle more readily from the system under the influence of gravity. Secondly, the molecules of a gas move with much greater freedom and in longer paths than do those of liquids or solids; consequently the amplitude of the Brownian motion of the particles is very much greater in an aerosol than in other disperse systems. This tends to increase the rate at which particles collide to form aggregates. Finally, in a given aerosol some particles of the disperse phase may be electrically neutral, while at the same time others may be charged either positively or negatively (62). In a liquid or solid disperse system all the particles are charged with the same sign. In all these respects, it would seem that an aerosol should be very much less stable than other forms of disperse systems. Experience has shown, however, that aerosols can be formed possessing a degree of stability comparable with that obtained in liquid systems.

Movement of Particles.

A particle suspended in a gas may move under the influence of the following forces:-

- (1) Forces which originate independently of the gas (e.g. gravitation, centrifugal action, an electric field).

(2) Forces which are the direct result of the molecular activity of the gas itself (e.g. Brownian movement).

When a liquid or solid particle is suspended in a gas it is subjected to a general bombardment by the molecules of the gas. If the particle is large when compared with the length of the mean free path of the gas molecules, the general effect of the molecular bombardment will be that of a uniform continuous pressure, exerted normally over the entire surface of the particle.

If the particle be moving through the gas, e.g. falling under gravity, the force of the molecular impacts will be greater in front of the moving particle than behind it by an amount which will depend upon the velocity of the particle. The particle will thus encounter a continuous uniform resistance to its motion which will become greater as the velocity of the particle increases.

If a gas be moving bodily, as in a convection current, it will by virtue of this resistance impart to particles suspended in it a velocity which will depend upon the velocity and resistance of the gas and the mass of the particles. The particles will thus move along a path which will be the resultant of that due to gravity or any other external force, and that due to the motion of the gas.

When, however, the particle is small compared with the mean free path of the gas molecules it will no longer encounter a continuously uniform pressure. It will tend to slip between the molecules, and will be driven hither and thither by the now irregularly distributed impacts of the gas molecules.

It is convenient to consider separately the behaviour of particles both larger than and smaller than the mean free spaces

of the gas.

Particles Larger than the Mean Free Spaces of the Gas.

The velocity with which small spherical particles move through a uniform viscous fluid (liquid or gas) under the influence of an external force (e.g. gravity) will be given by the expression:-

$$V = F/K$$

where F is the strength of the forces and K is the functional resistance of the particles in passing through the gas.

It has been shown by Stokes that

$$K = 6\pi\eta rv$$

where η is the viscosity coefficient of the gas,

r is the radius of the particle, and

v its velocity.

The resistance increases as the particle becomes larger or moves more rapidly. It is also proportional to the viscosity of the gas.

A particle will be pulled vertically downwards by gravitation with a force of

$$4\pi r^3 p g/3 \text{ dynes}$$

in air, or any other fluid, the force will be diminished by the buoyancy of the fluid, and will be

$$4\pi r^3 (p - p^1) g/3$$

where p is the density of the particle, and p^1 is the density of the fluid.

When the velocity with which the particle is falling is such that the resistance it encounters just balances the weight of the

particle it will continue to fall at that velocity. At this point,

$$6\pi\eta r v = 4\pi r^3(p-p^1)g/3$$

so that v , the ultimate constant velocity of the particle, will be

$$2r^2(p-p^1)g/9\eta$$

For a particle of a given substance falling in air ($p-p^1$) and will be constant, so that the velocity of the particle will be directly proportional to the square of the radius. Non-spherical particles fall in the position in which they encounter maximum resistance. Thus fine crystals fall with their longer axis horizontal, similarly a cubic crystal falls point downwards, a plate or disc in a horizontal position (51).

Stoke's Law assumes that the particles are spherical. This is true of liquids; but for many solid smokes the particles may consist of (say) cubic crystals, or of aggregates formed by coagulation.

The method of sedimentation to determine particle size can only be applied to relatively large particles, and if these are loosely packed aggregates having a considerable degree of complexity a normal density cannot be assumed and hence Stoke's Law cannot be applied with any degree of accuracy.

Particles that are Smaller than the Mean Free Spaces of the Gas.

When a particle smaller than 10^{-5} cms is suspended in a gas at ordinary pressure it will be smaller than the mean free spaces between the gas molecules. Consequently it will tend to slip between the molecules of the gas.

The velocity with which it will be driven through the gas will

therefore be greater than that given by Stoke's Law.

It has been shown by Cunningham (63) and Millikan(64) that $V = V^1(1 + K\lambda/r)$ where V is the true velocity and V^1 the velocity corresponding to Stokes Law. λ is the mean free path of the gas molecule, and r is the radius of the particles. K is a constant approximately equal to 0.86.

Brownian Movement.

Very small particles not only move more readily through the relatively coarse gas network, but are subject to a vigorous buffeting by the rapidly moving gas molecules. Consequently they are driven hither and thither, in a perpetual "Brownian" movement similar to but more violent than that described by particles suspended in a liquid. According to the Kinetic Theory the average kinetic energy of a particle in Brownian movement in a gas is the same as the average kinetic energy of the molecules of the gas ($\frac{1}{2}mV^2$). Owing to its greater mass its velocity is correspondingly smaller than that of the gas molecules.

The mobility of the finer particles probably play an essential part, also in promoting the coalescence of smoke or cloud particles and the flocculation of the corresponding aerosol.

Coagulation.

It has been established both theoretically and experimentally that the Brownian movement causes coagulation of aerosol particles at a rate proportional to the square of the number concentration, n (65). To a first approximation the rate is independant of particle size. The rate of decrease of number concentration is then

$-dn/dt = Kn^2$. The Smoluchowski constant $K = 4RT/3\eta n = 2.92 \times 10^{-10} \text{ cm}^3/\text{sec}$ in air at 20°C and η = viscosity of air = $1.82 \times 10^{-4} \text{ dynes-sec/cm}^2$.

The equation is exact for aerosols containing relatively large particles all of the same size, but has been found to hold satisfactorily for aerosols of non-spherical particles, of moderately non-uniform size. Although the frequency of collision between large and small particles is greater than between particles of the same size, this is largely compensated by the relatively small number of large sizes.

For small particles of radius comparable to the mean free path in air, the Cunningham correction must be applied to the simple coagulation equation as follows:-

$$-dn/dt = Kn^2(1 + 0.9L/r).$$

In air at 20°C the mean free path $L = 10^{-5} \text{ cm}$. Consequently, because of the Cunningham correction the coagulation rate is increased 9% for 1 micron particles and 90% for 0.1 micron particles.

When the coagulation equation holds approximately, it means that all or nearly all particles adhere on collision. A number of experiments justify the assumption of 100% collision efficiency of solid particles. Even in still aerosols, the observed coagulation is never less, and is usually greater, than the Smoluchowski constant. Attempts have been made to surface treat solid particles to reduce the collision efficiency. The only effect was to reduce the adhesion of the particles in bulk, so that the particles were more easily dispersed.

Collection of Accurate Samples from a Dispersion.

Practically all investigations dealing with dust involve collection of a truly representative sample of dust from a moving suspension and

the determination of the concentration and the distribution of size among the particles. Although the correct principles are known the collection of an accurate sample from a gas stream in the atmosphere remains a relatively difficult operation. The main difficulty is caused by the centrifugal effects which can make both the gas velocity and the distribution of dust across a section of the gas duct far from uniform.

For this reason it was considered advisable to use a chamber to contain the dust and to work on a batch process, thus insuring 100% accuracy in sampling, i.e. remove the variable of fluctuation in dust concentrations.

A check was made to confirm the efficiency of the T.P. deposits for 20 micron particles which is claimed to be 100% by the manufacturers (66). A cloud of silica particles was sampled by two T.P.s in series. A heavy deposit of particles down to 0.4 micron was formed in the first instrument but none in the second, so there was no doubt about the actual efficiency of the T.P. for sampling very fine particles.

Method of Measuring Particle Size.

The size of a spherical particle is defined completely by its diameter but the "size" of an irregular particle of dust depends on the particular property of the particle being considered. Different methods of particle size measurement assess different size-dependent properties, such as the volume, or surface, or resistance to motion in a fluid or power of scattering light.

Since the theories of the methods are derived for spherical particles the "size" of an irregular particle is conveniently expressed as the diameter of the sphere having the same volume, or surface, etc. Only for spherical particles will the sizes by different methods be the same. In the case of irregular particles the "sizes" differ not only according to the method of measurement but also, in some measurements, according to the orientation of the particles, for example in the case of the projected area.

Microscope Method.

The simplest method of determining the size of particles in the subsieve range (76 microns (200 B.S.) down to 0.4micron) is direct measurement to the dimensions of the magnified images of the particles seen under the microscope. The measurements are commonly made by a visual comparison of the areas of the images of reference circles. Down to sizes of two microns or less, the images are accurate magnifications of the particles and the microscope method is probably the most exact of all methods of sizing. As the limit of resolution (about 0.4 micron) is approached the particles appear larger than they actually are.

The size actually measured with a microscope is the diameter of the circle having the same area as the unmagnified projected image of the particle. This is termed the area diameter.

When the sample contains a range of particle sizes, a number size distribution is obtained by recording the number of particles corresponding to each size of reference circle. The characteristics

of these size distribution curves may be defined by the usual statistical methods, namely, the mean, the median and the mode.

The mean value represents the particle size corresponding to the centre of area (centre of gravity) of the area enclosed by the curve and the x-axis; the median value is the particle size at which the powder could be divided into two portions of equal number and the mode represents the most frequently occurring particle size, that is, the particle size corresponding to the peak of the size distribution curve. The number mean particle size which corresponds to the centre of area of the size distribution curve is obtained from the expression

$$\Sigma ND/N .$$

Determination of Concentration and Size Distribution.

A Vicker projection microscope equipped with a 4mm achromatic objective lens was used since the highest possible resolution is required to enable counts and size distribution estimations to be made down to the visible limit. A x 10 compensating eyepiece was used in the microscope and the counting carried out at a magnification of x 1125.

The particles were sized by comparing them with the numbered circles on the previously calibrated graticule, and entered in the appropriate size group. Each particle, often of irregular shape, was treated as an equivalent circle, so that it was in effect the cross sectional area which was compared with the circles on the graticule.

When making a size distribution count it was necessary to include 300-400 particles across the deposit on the cover circle. Since the

size distribution varies across the strip, this entailed in the case of more dilute suspensions the counting of a number of traverses.

When the dust concentration was being assessed the deposit was traversed horizontally across the field by means of the mechanical stage on the microscope. The particles were kept in focus by adjusting the fine focussing screw. The number of particles were counted in three strips equally spaced along the deposit, care being taken to traverse right across the deposit and to focus successively both on the underside of the cover glass and on the top of the slide, since a few large particles tended to fall from the cover glass and there was usually an appreciable air space between it and the slide.

Calculation of Results.

If for any particular T.P. head the length of deposit is L and the width of each strip counted is W , there will be L/W such strips in each deposit. If the average count across the deposits from each side is N_1 & N_2 and V is the volume of the whole sample then the number of p.p.c.c. is

$$\frac{N_1 + N_2}{V} \times \frac{L}{W}$$

for an actual case where $N_1 = 186$

$$V = 5.1 \text{ c.c.s}$$

$$N_2 = 190$$

$$L = .83 \text{ cms}$$

$$W = .0051 \text{ cms}$$

$$\text{then } \frac{186 + 190}{5.1} \times \frac{.83}{.0051} = 12,000 \text{ p.p.c.c.}$$

Procedure for using the T.P.

The T.P. could be used in conjunction with the photoelectric

cell (P.E.C.) systems or by itself. The procedure for filling the chamber with dust was as before. After sedimenting for 55 minutes a volume of the dust cloud, in proportion to the concentration of the dust, was withdrawn by lowering the T.P. head into the chamber and aspirating over a sample of the dust laden air. The dust was deposited on two microscopic glass circles in the T.P. head. The T.P. head was withdrawn from the chamber, the cover circles mounted on a microscope slide and the spray blown into the chamber. After the spraying period was over the T.P. head fitted with clean cover glass circles was again lowered into the chamber and a sample of the dust cloud withdrawn. From these samples the concentrations of the dust cloud before and after spraying could be found.

In a spray run using the T.P. the procedure outlined above was repeated at the end of 2 hours, 3 hours and 4 hours after the original charging of the chamber with dust. The samples withdrawn were mounted on microscope slides and examined under a Vicker projection microscope at a magnification of $\times 1125$.

Verification of the Homogeneity of the Dust Cloud.

To show that the T.P. samples withdrawn from the centre of the chamber were representative of the total dust cloud both in concentration and size distribution, samples were withdrawn from three positions in the chamber at a level with the P.E.C. housings. The samples were withdrawn as soon after one another as possible and a correction made to compensate for the alteration of the concentrations of the dust cloud with time. The samples were withdrawn after

3 hours and 5 hours sedimentation and the results obtained shown in Tables 12 and 13.

The agreement for dust concentration at the three levels was not as good as expected for the samples withdrawn after 3 hours but after 5 hours the concentrations agreed exactly. The size distribution of the particles at both these sampling times were found to be in very good agreement for the three positions and did not show any great change for the two different times.

These results show the homogeneous nature of the dust cloud in the chamber with regard to concentration and size distribution. This agreed with the results obtained using the P.E.C. systems which showed the dust cloud was homogeneous with respect to surface area over a period of sedimentation.

Investigation of the Mechanism of Sedimentation.

To show the amount of dust removed by spraying for four periods of two minutes it was necessary to investigate the behaviour of the dust cloud over a similar period of time when no spraying had taken place. The difference in concentration of the dust at the end of four hours when spraying had been carried out compared with the concentration of dust when sedimentation alone had taken place could be attributed to the spray.

To investigate the mechanism of sedimentation of the cloud of fine silica dust a sample was withdrawn every hour over a period of 12 hours. A dust cloud was again generated and left to settle for 12 hours before sampling was started. The cloud was then sampled

Table No. 12.

Results to show the Homogeneous Nature of the Dust Cloud in the Chamber.

Concentration at Different Depths.

Time	Position	Concentration (p.p.c.c.)	Concentration corrected for time (p.p.c.c.)
3hs 10mins	Top Posn.	16,100	
3hs 20mins	Middle Posn.	14,100	15,000
3hs 30mins	Bottom Posn.	15,500	14,000
5hs 10mins	Top Posn.	8,170	
5hs 20mins	Middle Posn.	7,700	7,700
5hs 30mins	Bottom Posn.	7,560	7,500

Table No. 13

Size Distribution at Different Depths.

Size Microns.	After 3 hs 10 mins Top Posn.	After 3 hs 20mins Mid Posn.	After 3 hs 30mins Bottom Posn.	After 5 hrs 10mins Top Posn.	After 5hs 20mins Mid Posn.	After 5hs 30 Bottom Posn.
0.4-0.8	18.5	21.5	11.6	24.7	18.2	19.6
0.8-1.6	46.5	51.0	55.4	41.3	44.0	41.2
1.6-2.4	18.2	18.9	18.4	19.3	21.5	21.6
2.4-3.2	10.7	7.1	9.6	8.7	8.9	9.9
3.2-4.0	5.8	1.3	3.8	3.3	5.9	6.0
4.0-5.0	2.1	.2	1.	1.9	.9	1.2
5.0-6.0	.2		.2	.8	.6	.5
	100	100	100	100	100	100

at hourly intervals over a 12 hour period. The samples were examined under the microscope and the concentration of the dust cloud calculated. The values of the concentration for the second period of 12 hours overlapped the concentrations for the first period of 12 hours and a graph showing the variation of concentration of the dust cloud in p.p.c.c. was constructed for a period of sedimentation of 19 hours.

Graph 21 is seen to follow the form of the graphs obtained for galvanometer deflection against time when the P.E.C. systems were used, viz., a steep section in the early stages of sedimentation gradually levelling off to show a slow rate of dust removal. Smoluchowski showed that the decrease in the number of particles per unit volume in suspension in air behave according to the law:-

$$-dn/dt = Kn^2$$

i.e. on integration $1/n - 1/n_0 = Kt$

Where n_0 = concentration of the dust on formation ,

n = concentration of dust at time t .

$1/n$ denotes the average space inhabited by a particle in the cloud at any instant of time. It is termed conventionally the particulate volume and n the particulate number.

From Graph 21 the values for the concentration of the MSC dust were obtained at hourly intervals over a period of sedimentation of 19 hours. From these concentrations the values for the expression $(1/n - 1/n_0)$ were calculated and plotted against time.

Graph 22 was obtained and it can be seen to fall into two distinct sections, as follows:-

(1) A period lasting for 10 hours, when the decrease in the number of particles with time is very rapid. (This is probably due mainly to the aggregation of the particles and corresponds to an increase in the average mass of the particles).

(2) A period from 10 hours onwards when the dust cloud is relatively stable and the number of particles diminishes very slowly, chiefly as a result of sedimentation.

Between those two stages there is a third intermediate stage of short duration in which both aggregation and settling operate.

Similar stages have been suggested by Whytlaw-Gray(67) for smokes of NH_4Cl , CdO , CuO and ZnO working from graphs of p.p.c.c. against age of smoke.

It was decided to use another form of silica dust to confirm the results obtained for MSC dust. The material chosen to form the dust was Lochaline Sand, a high-grade silica sand mined at Lochaline, Argyllshire for the manufacture of optical glass. A typical sample contained about 99.6-99.7% silica and 0.2% alumina, with traces of iron oxide.

A sample of Lochaline Sand (LAS) was ground for 2 hours in a mechanical agate mortar to reduce a proportion of the sand to very fine particles. The dust was then placed in an oven at 120°C and left to dry for 24 hours. The dried, finely ground sample was then treated as the MSC dust to produce a dust cloud in the chamber. 5 gs. of LAS were used in the dust-producing apparatus and a cloud

formed by blowing for 15 seconds. The method of sampling was as before and after the concentration of the dust had been calculated a sedimentation curve for LAS was constructed (Graph 23). This curve showed a slower rate of reduction in concentration (p.p.c.c.) than did the corresponding curve for MSC.

Construction of the graph for $1/n - 1/n_0$ against time showed the same distinct stages for the decrease of concentration with time (Graph 24). The duration of sedimentation of LAS was 25 hours and over this period three stages in the process of sedimentation could be identified.

(1) A period lasting for $6\frac{1}{2}$ hours when the decrease in the number of particles with time is rapid.

(2) A period from $6\frac{1}{2}$ hours to 19 hours when the number of particles diminishes slowly.

(3) A period from 21 hours to 25 hours when the decrease in concentration is almost imperceptible.

Between the three stages there are two intermediate stages of short duration.

As was mentioned earlier the value for K, the Smoluchowski constant, has been shown to be $4RT/3\eta = 2.92 \times 10^{-10} \text{ cm}^3/\text{sec}$ in air at 20°C and η , the viscosity of air = $1.8 \times 10^{-4} \text{ dynes-sec/cm}^2$. The value of K depends then upon the temperature, though actually the change for ordinary alterations of room temperature has been shown to be small.

The values of K for the different sections of the graphs for

the two dust clouds were obtained from the gradients of the lines and are shown in Table 14. The value of K is seen to increase as the concentration decreases for the two dust clouds but even at its minimum value $6.79 \times 10^{-9} \text{ cm}^3/\text{sec}$ it is much greater than the theoretical value of $2.92 \times 10^{-10} \text{ cm}^3/\text{sec}$. It has been found that the value for K derived by practical means is invariably greater than the value found theoretically.

At this stage it is of interest to note the experimental evidence produced by Whytlaw-Gray(68) when considering the effect of the shape of the particle on the rate of coagulation. The smokes used in his work were oleic acid, stearic acid and ferric oxide. The Smoluchowski constant, found for oleic acid and stearic acid, agreed closely with theory whilst that obtained for ferric oxide was found to be 30% greater. The stearic acid and oleic acid complexes, though not truly spherical, were of a compact form, whilst those of ferric oxide were loosely built chain-like structures formed of units which appeared "like beads on curly strings". This form of aggregate suggests the presence of electrostatic charge on the particles and it is suggested that this accounts for the rate of aggregation being different from the theoretical value.

The same reason would explain the high values of the Smoluchowski constants for MSC and LAS dust since it has been shown by many investigators that a cloud of silica dust generated in a manner similar to that employed by the author produced charged particles (76,77,80).

The difference for the values of the Smoluchowski constants for

MSC and LAS is thought to be explained by examination of the size distribution of the two dust clouds (Table 15). The values of K for LAS were less than those for MSC and the percentage number of the very fine particles (0.4 to 0.8 microns) is less for LAS. This is in agreement with theory which has shown for particles of the order of size of 1 micron that the coagulation rate is increased by 9% (63). Plate 10 shows the LAS dust after sedimenting for 1 hour.

Table No. 14.

Values of Smoluchowski's Constant, K.

Dust	Time Range	Concentration Range (p.p.c.c.)	Values of K
MSC	0 to 8 hs	41,000 to 3,680	$9.57 \times 10^{-9} \text{ cm}^3/\text{sec}$
	11 to 19 hs	3,680 to 800	$3.12 \times 10^{-8} \text{ cm}^3/\text{sec}$
LAS	0 to 6½ hs	39,000 to 6,000	$6.79 \times 10^{-9} \text{ cm}^3/\text{sec}$
	7 to 19 hs	6,000 to 1,550	$1.25 \times 10^{-8} \text{ cm}^3/\text{sec}$
	23 to 25 hs	1,400 to 800	$2.29 \times 10^{-8} \text{ cm}^3/\text{sec}$

Table No. 15.

Size Distribution of the Two Dusts after 1 Hour.

MSC		LAS	
Size in Microns	Percentage Number	Size in Microns	Percentage Number
0.4 - 0.8	24.5	0.4 - 0.8	11.5
0.8 - 1.6	37.5	0.8 - 1.6	33.2
1.6 - 2.4	18.5	1.6 - 2.4	23.8
2.4 - 3.2	10.1	2.4 - 3.2	14.1
3.2 - 4.0	4.0	3.2 - 4.0	8.8
4.0 - 5.0	3.75	4.0 - 5.0	6.1
5.0 - 6.0	1.75	5.0 - 6.0	1.9
6.0 - 8.0		6.0 - 8.0	.4
8.0 - 10.0		8.0 - 10.0	.2
	100		100

Conclusions.

The concentration (p.p.c.c.) of the cloud of MSC and LAS dust was shown to decrease rapidly at the higher concentrations but as the concentration of the dust cloud fell the rate of decrease in concentration decreased until it was almost imperceptible.

Application of Smoluchowski's Law distinguished different stages in the decrease in concentration of the dust cloud with time. The values of K for the different stages were calculated and they were found, in every case, to be greater than the theoretical value. The reasons for this are thought to be as follows:-

- (1) The non-uniform nature of the dust cloud from the point of view of particle size.
- (2) The electrostatic charges which will exist on the dust particles and which have been shown to influence the aggregation (see Section 5).

The difference in the values of K found for the clouds formed from MSC and LAS dust has been attributed to the difference in the proportion of very small particles, <1 micron, which will coagulate quicker due to their greater mobility.

SECTION 4.Effect of Sprays on Dust in Suspension in the Chamber.

As has already been indicated, insufficient information was obtainable on the effect of spraying on the characteristics of the dust cloud in the chamber when the light extinction method was used. To obtain information on the alteration of the concentration of the cloud, in p.p.c.c. and the size distribution of the particles in the cloud, spray tests were carried out using the T.P. to determine the characteristics of the cloud. Most of the tests already carried out using the light extinction method to measure the dust concentration were duplicated using the T.P.

The first spray test, using the T.P. as already described, was carried out with water at 62 lb./in.^2 spraying for four periods of two minutes duration at the end of 1, 2, 3, and 4 hours after the chamber had been charged with dust. The results obtained are presented in Table 16 and show the reduction in dust concentration at different concentrations of the dust cloud. It was assumed that no reduction in concentration (p.p.c.c.) due to sedimentation and aggregation takes place between the two sampling times.

The reasons for making this simplifying assumption are as follows:-

(1) The conditions existing in the chamber during this period are very different from the conditions for which the sedimentation curve was constructed, i.e. the turbulence in the chamber during spraying, and for a period after spraying will tend to prevent the aggregation and sedimentation of the particles.

Table No. 16.

Effect of Spraying on Dust Suppressed.

Spray Nozzle No. 1.

Pressure lb./in. ² .	Duration of Spraying	Time	Concentration (p.p.c.c.)		
			Before Spray	After Spray	Reduction
62	2 mins	1 h	17,080	12,450	4,630
	2 mins	2 hs	5,220	3,220	2,000
	2 mins	3 hs	2,370	1,700	670
	2 mins	4 hs	982	557	425

(2) The alteration of the size distribution and concentration caused by spraying will also affect the rate of removal of particles from suspension by altering the tendency to aggregate and sediment.

The number of particles removed by the spray is obtained by subtracting the concentration of the dust cloud before and after spraying, no allowance being made for decrease in concentration by sedimentation and aggregation.

The amount of dust removed at the different spraying times will not be a simple function of the concentration, as the size distribution of the dust cloud changes over the four spraying periods (see Section 5).

This will result in a decrease in the efficiency of collection of the particles by the spray droplets.

The number of particles of dust removed by spraying will decrease with time for two reasons.

(1) The concentration is greater during the earlier spraying periods and the possibility of the water droplets making contact with the dust particles will therefore be greater.

(2) The size distribution of the particles is altered with time (see Section 5), the larger dust particles and aggregates being removed in the earlier spraying periods.

Effect of Altering Direction of Spraying.

Spray tests were carried out on the dust cloud to confirm the results obtained by the light extinction method, that no

advantage was derived by spraying the dust cloud from above or below.

The concentrations for the two runs and the conditions under which the runs were carried out are presented in Table 17.

The results show that spraying upward through the dust cloud is as effective in reducing the dust concentration as spraying downward through the cloud under the same conditions of throughput and atomisation.

The explanation for this has been given already in Section 2.

The efficiency of removal of dust by different spray conditions is represented by expressing the final dust concentration as a percentage of the initial concentration. For this figure to be proportionally representative of the efficiency of dust suppression at different initial concentrations, the decrease of concentration with sedimentation and duration of spraying would have to be a linear function of time. This is not so, but the figure provides a suitable means of comparing the efficiency of dust removal when the original concentrations are approximately the same at the beginning of a spraying test.

The Conditions affecting Efficiency of Collection.

According to Davies(69) exact data for the impingement of particles upon spheres have not been worked out but precisely similar conclusions relating to impingement upon cylinders apply.

Impingement of Dust Particles upon a Cylindrical Rod.

If a cloud of dust particles is blown towards a cylindrical rod, transversely to the flow, the maximum number that could hit it is

Table No. 17.

Effect of Direction of Spraying on Dust Suppressed.

Direction of Spray- ing	Pressure lb./in. ²	Duration of Spray- ing	Time	Concentration (p.p.c.c.)		Percentage Remaining
				Before Spray	After Spray	
Downwards	62	2 mins	1 h	25,600	15,850	13.0
		2 mins	2 hs	11,700	9,530	
		2 mins	3 hs	6,560	6,250	
		2 mins	4 hs	5,550	3,340	
Upwards	62	2 mins	1 h	24,400	17,500	12.8
		2 mins	2 hs	14,150	9,200	
		2 mins	3 hs	9,100	6,100	
		2 mins	4 hs	-	3,120	

$2 N U_0 (R + a)$ particles per second on each centimetre of its length, where N is the concentration of airborne particles p.p.c.c., a is the radius of the particle, R the radius of the rod and U_0 the velocity of the particle. This would hold in reality only for very heavy particles for which the particle parameter P was sufficiently large. In fact, the quantity striking the wire is smaller than this, and depends on the parameter P , the ratio of particle radius to wire radius, and on the type of flow. The ratio of particle to cylinder radius also affects the flow field causing the particle trajectory to curve away from the cylinder to a greater extent than is found from the stepwise calculation, taking the particle as a massive point. This is less important, however, than the interception factor, which allows for collision occurring when the surface of the particle - not its centre - meets the cylinder and depends on a/R .

For this reason there is not a unique curve of collection efficiency E against P for a given Reynolds number, but rather a family of curves, with each member characterised by the value of a/R , and tending, when this ratio becomes small, towards a curve for point particles. The efficiency can therefore be written as

$$E = F(P, Re, a/R)$$

A large velocity increases both the Reynolds number and the particle parameter, so that on both counts the efficiency of collection increases. An increase in the radius of the cylinder R , however, other things being equal, has an adverse effect on both P and a/R . It also increases the Reynolds number but this

effect is as a rule of less importance.

In his estimate of efficiency of collection of dust particles by freely falling droplets, Davies (69) was guided by Vasseur's (70) results at Reynolds number exceeding 100 and by curves extrapolated from the data for cylinders at lower values.

In this way curves of Graph 25 were constructed showing the proportion of particles (E per cent) collected by a drop falling vertically, out of all those lying in its path (cross sectional area $\pi(d^2/4)$).

It is clear that the optimum diameter of water droplet is between 0.5 and 1 mm. Small droplets are less efficient because they fall so slowly that they do not collide with the dust particles, but push them sideways in passing. The lower efficiency of large droplets is explained as follows. The particle parameter P is inversely proportional to the droplet diameter so that particles of a given size have a smaller value of P relative to the larger droplets. Impingement is, of course, less efficient for a smaller value of P. This effect outweighs the increase in terminal velocity, which is very slight for droplets greater than 4 mm in diameter, so that impingement upon large droplets decreases as droplet size increases above the optimum value. From Graph 25 it can be seen that suppression of dust particles having radii below 5 microns is very poor and gravitational scrubbers are obviously of no use for fine dust.

Improvement in this direction can be achieved only by increasing the relative velocity between dust particle and spray droplet.

Effect of Atomisation on Suppression of Dust.

It has been established by different authorities that the efficiency of wetting of fine dust, which is not airborne, is improved by increasing the atomisation of spray (24,25).

It was decided to investigate the effect of increasing the atomisation of a spray on the efficiency of suppression of airborne silica dust. By changing the pressure of the water in the spray unit the degree of atomisation was altered and graphs representing this change in atomisation with pressure are shown in an earlier section of the thesis.

Tests were carried out at five different pressures over a wide range of atomisation to show how the efficiency of dust removal was affected by atomisation. The throughputs for the particular pressures used were found from the graph of \sqrt{P} against throughput and the duration of spraying altered so that 152 c.c.s of water were added during the spraying period.

Table 18 shows the pressure, duration of spraying and concentration at the different spraying times.

From these results it can be seen that the amount of dust removed by spraying is increased by increasing the water pressure and hence the atomisation. These results are in accord with the theory which states that the efficiency of collection of dust particles by water droplets is proportional to

$$pVd^2/D \quad \text{where } p = \text{density of liquid.}$$

V = velocity of contact.

Table No. 18.

Effect of Atomisation on Dust Suppression.

Pressure lb./in. ²	Duration of Spray- ing	Time	Concentration(p.p.c.c.)		Percentage Remaining
			Before Spray	After Spray	
36	2mins 45secs	1 h	16,460	17,850	48.0
	2mins 45secs	2 hs	14,000	13,220	
	2mins 45secs	3 hs	10,280	10,200	
	2mins 45secs	4 hs	2,820	7,920	
46.5	2mins 33secs	1 h	17,620	12,180	14.4
	2mins 33secs	2 hs	9,700	10,200	
	2mins 33secs	3 hs	7,190	4,830	
	2mins 33secs	4 hs	4,070	2,530	
53	2mins 20secs	1 h	14,000	10,400	17.5
	2mins 20secs	2 hs	7,500	5,250	
	2mins 20secs	3 hs	5,550	3,630	
	2mins 20secs	4 hs	3,570	2,460	
62	2mins	1 h	17,080	12,450	5.3
	2mins	2 hs	5,220	3,220	
	2mins	3 hs	2,370	1,700	
	2mins	4 hs	982	557	
78	1min 50secs	1 h	18,500	9,640	6.1
	1min 50secs	2 hs	8,720	5,240	
	1min 50secs	3 hs	3,880	2,270	
	1min 50secs	4 hs	1,215	946	

d = diameter of particle.

D = diameter of droplet.

Increasing the atomisation increases the velocity of the droplet and decreases the average droplet size (see Section 1). Both these factors increase the efficiency of collection according to theory.

It is interesting to note that at the lowest pressure (36 lb./in.²) the first period of spraying results in an increase in concentration (p.p.c.c.). This seems to indicate that the aggregates are broken up to some extent by the water droplets, and it would be unreasonable to assume that breaking up does not also occur when higher water pressures are used.

In the case of the two highest pressures used 62 lb./in.² and 78 lb./in.² the amount of dust knocked down by the water is almost the same. This is because the spray nozzle almost reaches its maximum efficiency of atomisation at 62 lb./in.² and an increase of pressure to 78 lb./in.² results in very little change in atomisation. This is shown by size distribution curves for the water droplets produced by spray nozzle No. 1 at different pressures and the values for the average droplet size presented in Section 1 of the thesis.

The Effect of Altering the Droplet Velocity and the Average Droplet Size.

From the results presented above it is evident that for the same volume of water the dust is more easily suppressed as the spray is more fully atomised.

Increasing the pressure of the water and therefore the atomisation alters the following three characteristics of the spray:-

- (1) throughput;
- (2) average droplet size of the spray;
- (3) velocity of the droplets.

In each of the runs already carried out the duration of spraying was adjusted so that the same volume of water was added to the chamber. The variables were then the size and velocity of the droplets. The greater the pressure the smaller the average droplet size and the greater the velocity. It was decided to determine the effect of altering one of the variables while the other remained constant to show their effect independently. To obtain the necessary conditions two spray nozzles were used, previously calibrated for throughput and droplet size.

Effect of Altering Droplet Size.

The velocity of the water droplets issuing from the nozzle was determined by assuming that during spraying the spray orifices "ran full". This assumption is not valid for swirl atomisers of the type used, but since the assumptions applied to both nozzles comparative velocities were obtained which could be taken as very nearly correct.

Calculation of the area of the orifices for nozzles No.1 & 2 gave their ratio as 1.121 :1. The pressure chosen for nozzle No.2 was 62 lb./in.² which corresponded to a throughput of 73 c.c.s per minute. For the droplets from nozzle No.1 to have the same initial velocity a throughput of 65 c.c.s per minute had to be used which corresponded to a water pressure of 46.5 lb./in.²

Table 19 shows the spray conditions necessary for comparison of the effect of different average droplet size when the initial velocity was the same. The results, (Table 20) show that a decrease in the average droplet size results in an increase in the amount of dust removed from suspension in the air when the initial velocity of the droplets remains the same. This is again in agreement with the formula relating efficiency of collection to the variables in the spray droplets:-

$$E \propto pVd^2/D$$

The improvement in the efficiency of collection will be cancelled out to a certain extent because the smaller droplets lose their initial velocity and attain their terminal velocity more quickly. It has been shown (Graph 25) that droplets of the size range produced by the spray nozzle do not remove dust below 5 microns to any great extent when falling at their terminal velocity. It will only be at the high velocities that the small droplets are effective.

Effect of Altering Velocity.

The conditions for the production of sprays from nozzles No.1 and 2 which had the same average droplet size were found by interpolating the result obtained for variation of average droplet size of spray with pressure. The pressures corresponding to the same droplet size from nozzles No.1 and 2 were produced in the pressure chamber of the spray unit and the duration of spraying altered to add the same volume of water to the chamber, 152 c.c.s at each spraying period.

The conditions for the sprays are shown in Table 21.

Table No. 19.

Effect of Altering Droplet Size on Dust Suppression.

Nozzle No.	Pressure	Through-put	Average Droplet Size	Duration of Spray	Velocity
1	46.5 lb./in. ²	65 c.c.s/min	69 Microns	2mins 25secs	72,000 cm/min
2	62 lb./in. ²	73 c.c.s/min	48 Microns	2mins 5secs	71,500 cm/min

Table No. 20.

Nozzle No.	Pressure	Concentration (p.p.c.c.)		Percentage Remaining
		Before Spray	After Spray	
1	46.5 lb./in. ²	24,500	20,300	16.7
		20,200	15,200	
		10,000	8,880	
		4,620	4,080	
2	62 lb./in. ²	21,500	16,900	5.5
		6,670	6,420	
		2,790	2,640	
		2,090	1,190	

The results for the reduction in dust concentration are shown in Table 22. These results show the influence of velocity to be a very important factor in the suppression of the dust. It should be pointed out that the droplets formed in the sprays do not behave as individual droplets as far as their motion is concerned but move in an envelope of air and so maintain their velocity for a considerably longer time than would be expected for their size. This increase in velocity will be particularly effective in a closed space such as exists in the dust chamber, creating turbulence and increasing the velocity of impact between the water droplets and the airborne particles.

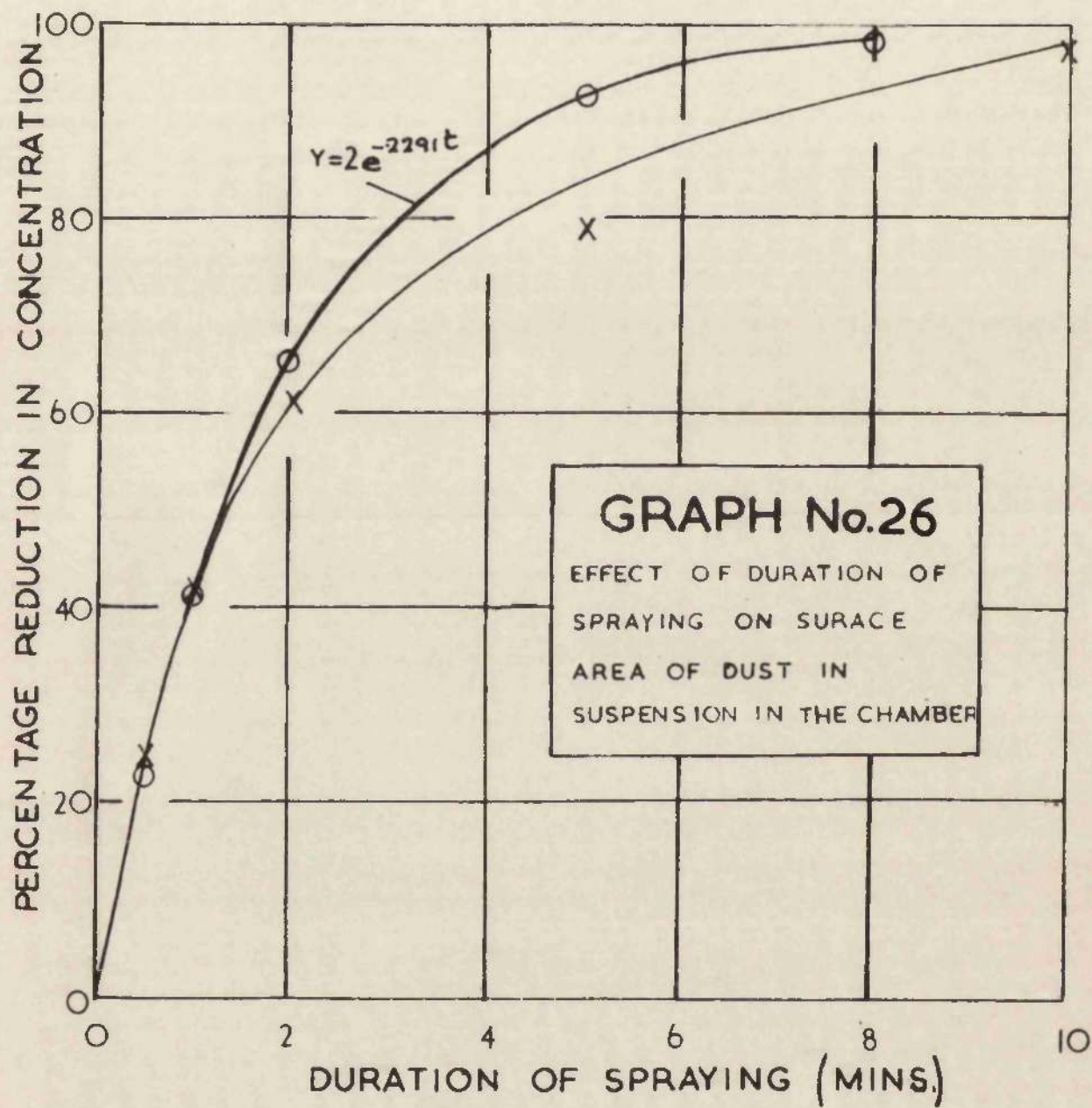
Variation of Concentration with Duration of Spraying.

A series of tests were carried out to determine the effect of altering the duration of spraying on the concentration in p.p.c.c. A similar series of spray tests had been carried out using the light extinction method to estimate the dust concentration.

The durations of time chosen for spraying were 30 seconds, 1 minute, 2 minutes, 5 minutes, 10 minutes and 15 minutes. The results obtained are shown in Table 23. A graph of percentage reduction of the concentration of the dust in p.p.c.c. against duration of spraying was constructed (Graph 26A).

Comparison of this graph with the graph obtained for the percentage reduction in surface area against duration of spraying obtained by the light extinction method (Graph 26) shows the percentage reduction in surface area to exceed the percentage reduction in p.p.c.c. for the same duration of spraying.

The reason for this is attributed to the following three factors:-



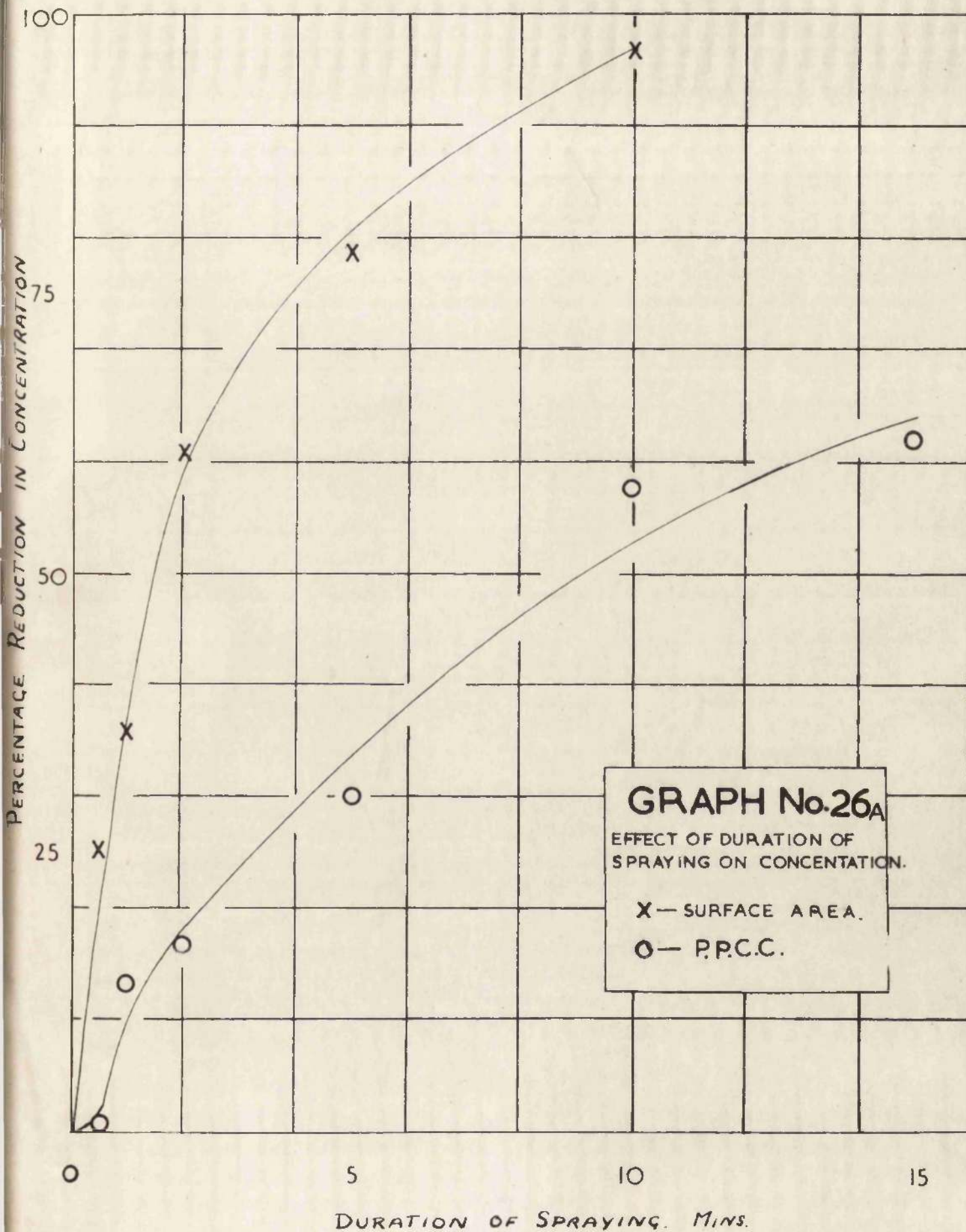


Table No. 21.

Effect of Altering Velocity on Dust Suppression.

Nozzle No.	Pressure lb./in. ²	Throughput	Average Droplet Size	Duration of Spray	Velocity
1	67	77c.c./min	55 Microns	2mins	84,500cm/min
2	43	61c.c./min	55 Microns	2mins30secs	59,500cm/min

Table No. 22.

Nozzle No.	Pressure lb./in. ²	Concentration (p.p.c.c.)		Percentage Remaining
		Before Spray	After Spray	
1	67	22,000	16,100	3.3
		6,750	4,160	
		3,070	2,200	
		1,270	720	
2	43	23,400	16,900	21.6
		16,900	12,200	
		8,870	6,900	
		-	5,050	

Table No. 23.

Effect of Duration of Spraying on Dust Suppression.

Duration of Spray- ing	Pressure lb./in. ²	Concentration (p.p.e.c.)			Percentage Reduction
		Before Spray	After Spray	Reduction	
30 secs	62	24,000	21,000	2,500	10.4
1 min	62	28,000	21,300	6,700	23.9
2 mins	62	23,400	16,900	6,500	27.8
5 mins	62	25,200	14,450	10,750	42.7
10 mins	62	22,930	6,840	15,090	66.0
15 mins	62	25,000	6,320	18,680	74.8

(1) The removal of the larger particles and aggregates in the first period of spraying with a correspondingly large decrease in the projected area of the dust cloud.

(2) The breaking up of some of the larger aggregates to give a number of smaller particles which are recorded in the concentration as found by the T.P.

(3) After spraying for about 5 minutes, only the very small particles and aggregates are left in suspension, i.e. $97.6\% < 2.4$ microns. Particles of this order of size and smaller do not follow the geometrical law of scattering light with the result that these smaller particles are underestimated with respect to projected area (71,72).

Effect of S/A Agents on the Amount of Dust Suppressed.

Details of the S/A agents used have already been given in Section 1 of this thesis.

To determine the effect of S/A agents on the dust suppressed in the chamber, tests were carried out using aqueous solutions of S /A agents to form the spray.

S/A agents were selected from different classes to cover most of the better known types. Most of the S/A agents used were supplied by I. C.I. Ltd., along with data on the S/A agents including the variation of surface tension with concentration. The variation of surface tension with concentration of the S/A agent is shown in graphs 5 and 6. The concentration used in the spray runs was 0.5% which gives the minimum surface tension available for an aqueous

solution of the different S/A agents.

Spray runs were carried out in the usual manner at a pressure of 62 lb./in.² for the different S/A agents and the results shown in Table 24 obtained.

The solutions in order of efficiency are then:-

1.	0.5% Lissapol L.S.	12.1%
2.	0.5% Fixanol C	12.25%
3.	0.5% Lissapol NDB	12.5%
4.	Water alone	13.0%
5.	0.5% Calsolene Oil	13.9%
6.	0.5% Alcopol O in Aqueous Solution	13.9%
7.	0.5% Lissapol C	17.6%
8.	0.5% Alcopol O in Alcohol Solution	19.4%
9.	0.5% Sterox SK	22.0%

Most of the S/A agent solutions are seen to have approximately the same efficiency in suppressing the dust as water alone. There are three exceptions to this, Lissapol C, Alcopol O and Sterox SK, all giving a lower efficiency than a spray of water alone.

The reason for the low efficiency of Alcopol O in alcohol solution is thought to be the higher rate of evaporation of the droplets from this solution compared with other solutions owing to the small percentage of alcohol in the solution. The spray run using 0.5% Alcopol O in aqueous solution showed a higher efficiency than the 0.5% Alcopol in Alcohol solution. The small percentage of

Table No. 24.

Effect of S/A Agents on Dust Suppression.

Type of S/A Agent	Pressure of Solu- tion lb./in. ²	Conc. of Solution	Time	Concentration(ppm.)		Percent- age Remaining
				Before Spray	After Spray	
Water	62	-	1 h	25,600	15,850	13.9
			2 hs	11,700	9,630	
			3 hs	6,560	6,250	
			4 hs	5,550	3,340	
Non-ionic	62	0.5% NDB	1 h	27,600	23,000	12.5
			2 hs	15,900	10,200	
			3 hs	8,850	4,380	
			4 hs	-	3,440	
Non-ionic	62	0.5% Sterox SK	1 h	23,000	15,400	22.6
			2 hs	13,600	8,750	
			3 hs	8,280	5,820	
			4 hs	5,190	5,200	
Anionic	62	0.5% Alecopol O (Aqueous)	1 h	26,000	19,400	13.9
			2 hs	18,600	11,200	
			3 hs	9,700	6,700	
			4 hs	5,350	3,600	

Table No. 24 (contd.)

Type of S/A Agent	Pressure of Solu- tion lb./in. ²	Conc. of Solution	Time	Concentration(p.p.c.)		Percent- age Remaining
				Before Spray	After Spray	
Anionic	62	0.5% Aiscopol O (Alcohol)	1 h	25,500	20,900	19.4
			2 hs	13,180	10,800	
			3 hs	9,020	7,730	
			4 hs	5,450	4,950	
Anionic	62	0.5% Calsolene Oil	1 h	26,000	22,000	13.9
			2 hs	16,900	12,100	
			3 hs	10,700	7,500	
			4 hs	6,500	3,620	
Anionic	62	0.5% Lissapol G	1 h	26,500	18,500	17.6
			2 hs	13,600	10,500	
			3 hs	9,050	6,450	
			4 hs	6,970	4,650	
Anionic	62	0.5% Lissapol LS	1 h	23,800	14,700	12.1
			2 hs	13,200	8,430	
			3 hs	7,820	5,520	
			4 hs	4,950	2,880	

Table No. 24 (contd.)

Type of S/A Agent	Pressure of Solution lb./in. ²	Conc. of Solution	Time	Concentration(pp.m.)		Percent- age Remaining
				Before Spray	After Spray	
Anionic	62	0.5% Permal BX	1 h	24,600	19,300	18.3
			2 hs	13,750	11,250	
			3 hs	10,080	8,100	
			4 hs	6,430	4,500	
Cationic	62	0.5% Fixanol C	1 h	21,900	14,100	12.25
			2 hs	9,870	7,370	
			3 hs	5,130	4,880	
			4 hs	3,500	2,680	

alcohol in the spray droplets will result in an increase in the droplet vapour pressure.

The approximate rate of evaporation of small droplets is given by the expression

$$-ds/dt = 8 \sqrt{pMD/PRT} = C$$

where S = droplet surface, T = time, p = droplet vapour pressure, M = droplet vapour molecular weight, D = droplet vapour diffusion coefficient in air, P = droplet density, R = molar gas constant, and T = absolute temperature.

Application of this formula to the vapour pressure of water at 15°C and a 0.3% alcohol solution at 15°C shows the alcohol to have a 4% higher rate of evaporation.

Calculation.

Vapour pressure of water at 15°C = 12.8 mm

Vapour pressure of 0.3% alcohol solution

at 15°C (From Raoult's Law) = 13.26 mm

Percentage increase in evaporation rate

$$= \left(\frac{13.26 - 12.8}{12.8} \right) \times 100\%$$

$$= \underline{\underline{4\%}}$$

Any increase in the rate of evaporation will result in a decrease in the number of the smallest droplets, which will quickly evaporate. Since the high-speed small droplets are considered to be the most efficient removers of the dust particles a decrease in efficiency of suppression will result.

The effect of different S/A agents on the degree of atomisation

of the solution is presented in Section 1 of this thesis; These results show that atomisation is independent of the type of S/A agent used. When the pressure was 62 lb./in.² and the concentration of the S/A agent was 0.5%.

It is suggested that the efficiency of a spray in suppressing the dust is due to:-

- (1) the degree of atomisation of the solution;
- (2) the rate of evaporation of the droplets;
- (3) the velocity of the droplets;
- (4) the size of the water droplets;
- (5) other factors, possibly electrical.

The Effect of S/A Agents at Low Water Pressure.

The results obtained using a 0.5% solution of Lissapol NDB at 62 lb./in.² showed an increase in dust suppression which could be accounted for by the slight increase in atomisation due to the S/A agent. It was decided to compare the efficiency of water at 46.5 lb./in.² with that of an 0.5% solution of Lissapol NDB at the same pressure. The reason for doing this was that the S/A agent was found in earlier work to be more effective at lower pressures in increasing the atomisation and would therefore be expected to result in a greater increase in dust suppression. The conditions for the spray runs and the results obtained are shown in Table 25.

The results show an increase in the efficiency of suppression when the S/A agent is included in the spray solution at 46.5 lb./in.² The efficiency of the S/A agent solution is not so great as that of water at 62 lb./in.²

Table No. 25.

Effect of S/A Agent at Low Pressure.

Pressure lb./in. ²	Duration of Spraying	Conc. of S/A agent	Time	Concentration (p.p.c.c.) Before After Spray Spray		Percentage Remaining.
46.5	2mins. 33secs	-	1h	17,620	12,160	14.4
		-	2hs	9,700	10,200	
		-	3hs	7,190	4,830	
		-	4hs	4,070	2,530	
46.5	2mins 33secs	0.5%NDB	1h	17,920	14,800	6.5
		0.5%NDB	2hs	10,950	7,140	
		0.5%NDB	3hs	5,020	4,000	
		0.5%NDB	4hs	2,745	1,160	
62	2mins	-	1h	17,050	12,460	3.3
		-	2hs	5,220	3,220	
		-	3hs	2,370	1,700	
		-	4hs	982	557	

The results obtained for atomisation under the conditions used in the spraying runs showed that a pressure of 46.5 lb./in.² and 0.5% Lissapol NDB gave a spray which had approximately the same average droplet size and distribution as a spray formed from water at 62 lb./in.² These two sprays differed in the velocity of the droplets, which accounts for the higher efficiency of the water at 62 lb/in.²

The efficiencies of the sprays in suppressing the airborne dust are then seen to be in line with the efficiencies of atomisation of the spray solution.

The efficiency of suppression of an airborne dust can be increased by

- (1) increasing the water pressure.
- (2) decreasing the surface tension by adding a S/A agent.

This method is particularly effective at low water pressures when the atomisation is relatively low.

Conclusions.

The fine silica dust cloud has been shown to be affected by spraying and some of the dust removed from suspension. The amount of dust removed is increased when

- (1) the duration of spraying is increased;
- (2) the degree of atomisation is increased;
- (3) the velocity of the spray droplets is increased;
- (4) the average droplet size of the spray is decreased;
- (5) a S/A agent is included in the spray solution at a low water pressure.

The percentage reduction in concentration (p.p.c.c.) is shown to be less than the percentage reduction in surface area. The reason is thought to be the removal of the larger particles and aggregates from suspension by the sprays.

No solution of S/A agent is found to be superior to water alone in suppressing the dust at 62 lb./in.² Some solutions were less effective. In the case of Alcopol 9 in alcohol solution the decrease in efficiency is attributed to the increased rate of evaporation of the spray droplets.

SECTION 5

Investigation of the Size Distribution of Airborne Dust.

The size of the airborne dust is recognised to be an important factor in the harmfulness of a dust cloud. The size distribution of the dust cloud being considered here was thought to be affected by:-

- (1) duration of suspension of the dust cloud in the chamber;
- (2) spraying with aqueous solutions. The dust samples obtained when the T.P. was used to estimate the concentration of the dust cloud were used to determine the size distribution of the dust in suspension in the chamber. Approximately 400 particles were estimated in the construction of a size distribution curve. The size distribution of the dust found by the T.P. and optical microscope represented the size distribution of the dust in the chamber since it has been established that no aggregation takes place on the microscopic cover circles(73).

Variation of Size Distribution with Time.

The variation of the size distribution of the particles and aggregates in the dust cloud was first investigated. The samples used in the construction of the concentration versus time curves for MSC dust were used in this work and the results obtained for the size distribution are shown in Table 26 for sedimentation over a 12 hour period. The results are also represented in histogram form in Graph 27.

The results show that the size of the aggregates increased

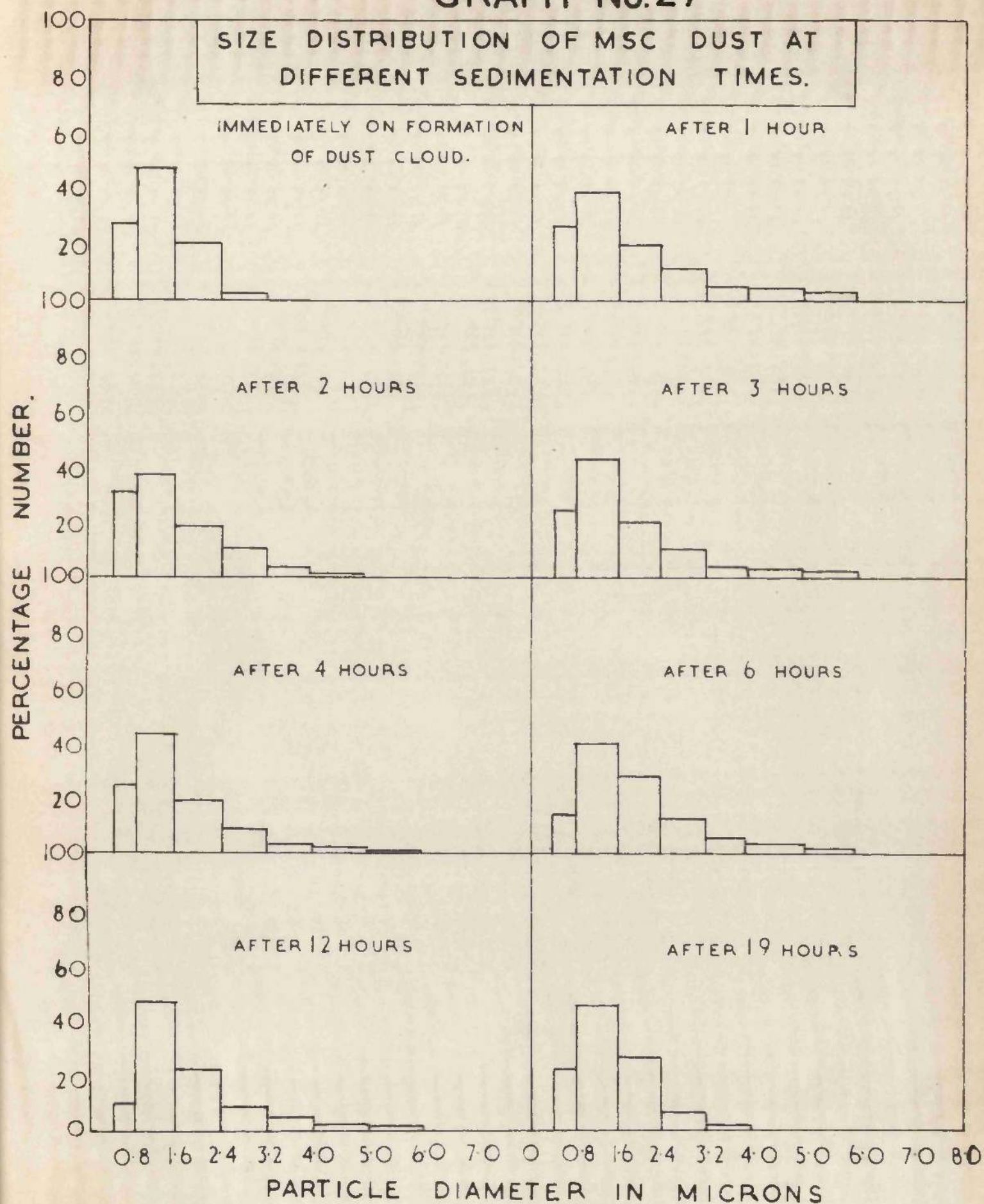
Table No, 26

Effect of Duration of Sedimentation on Size Distribution.

Size Microns	Immediately on formation	After 1h	After 2hs	After 3hs	After 4hs	After 6hs	After 12hs
0.4-0.8	28.1	24.5	30.7	23.3	24.5	13.0	10.4
0.8-1.6	47.8	37.5	36.7	41.6	43.0	39.0	47.4
1.6-2.4	20.9	18.5	18.7	19.0	18.8	27.4	23.3
2.4-3.2	3.2	10.1	9.9	9.5	8.2	11.4	9.6
3.2-4.0		4.0	3.8	2.9	3.4	5.4	5.7
4.0-5.0		3.75	0.2	2.0	1.8	3.25	1.9
5.0-6.0		1.75		1.7	0.3	0.25	1.7
	100	100	100	100	100	100	100

PERCENTAGE NUMBER

GRAPH No.27



during the first hour in suspension but after the first hour and up till the twelfth hour very little alteration in the size distribution of the dust occurred. Plates 2 and 3 show MSC dust immediately on formation and after one hour.

This lack of variation in the size distribution may be due to one or more of the following factors:-

(1) The dust particles settle out of suspension at the same velocity irrespective of their size. This is not unreasonable, since the larger particles are invariably aggregates (cf. original size distribution with size distribution after one hour), and have consequently a much lower density and terminal velocity than a solid particle of the same area diameter.

(2) The small particles and aggregates combine to form larger aggregates (>3 microns) which quickly fall from suspension owing to their relatively high terminal velocity. The smallest particles (ca. 1 micron) will combine to form aggregates more readily owing to their Brownian motion. This would account for the decrease in the proportion of 0.4 - 0.8 micron particles after sedimenting for 12 hours, instead of an increase, which would be expected if sedimentation were the only mechanism taking part in the decrease of the number of dust particles in suspension.

The latter explanation is supported by the growth of the particles and aggregates from their size on formation of the dust cloud to their size at the end of one hour. It is unlikely that the aggregation ends after one hour, yet no increase in the size

of the particles can be detected. In further support of this explanation is the fact that after sedimenting for approximately 19 hours, 98% of the dust particles are less than 3.2 microns in diameter. This shows that the larger particles do indeed settle out more quickly than the smaller ones. This fact is masked, at the higher dust concentrations, by the aggregation of the smaller particles to larger ones to give the same size distribution during the first 12 hours.

The effect of aggregation is most readily seen by inspection of the "tails" of the histograms. Immediately on formation the histogram is compact, the maximum sized particle being ca. 3 microns, but as the aggregation proceeds the size of the largest particle increases. Since no particle above 6 microns was detected over the whole period of sedimentation, it appears that the particles fall out of suspension relatively quickly when they reach a certain size.

Thus the decrease in the number of particles in suspension in the chamber is due to two factors:-

- (1) Aggregation of the small particles to form larger aggregates;
- (2) Sedimentation of the larger aggregates from suspension.

There is little doubt that only very few particles actually hit the solid walls of the chamber during sedimentation, most of them being surrounded by a layer of air and failing to strike the walls. Larger particles have a better chance of impact than smaller

because of their inertia.

The Effect of Spraying on the Size Distribution.

It became evident on examining the dust samples obtained by the T.P. for the effect of sprays on the dust cloud that not only was the concentration (p.p.c.c.) affected by the spray droplets but the size distribution of the dust particles was also altered. A spray test was carried out using water at 62 lb./in.² and spraying for four two-minute periods at the end of 1, 2, 3 and 4 hours after the chamber had been charged with dust. The results obtained for the size distribution are shown in Table 27 and also in the histograms in Graph 28.

These results show very clearly the preferential removal of the dust particles and aggregates. The removal of the larger aggregates will be due to two factors:-

(1) The larger the dust particle or aggregate the greater its inertia and hence the greater the chance of its coming into contact with a droplet of water.

(2) The larger aggregates are broken up into smaller particles and aggregates by contact with the water droplets or by the turbulence in the chamber due to the water droplets passing through the chamber at high velocity. Neither one of the above two factors is thought to be totally responsible for the removal of the larger aggregates, each factor playing some part.

Variation of Efficiency of Removal of Particles with Particle Size.

It is generally accepted that the efficiency of removal of

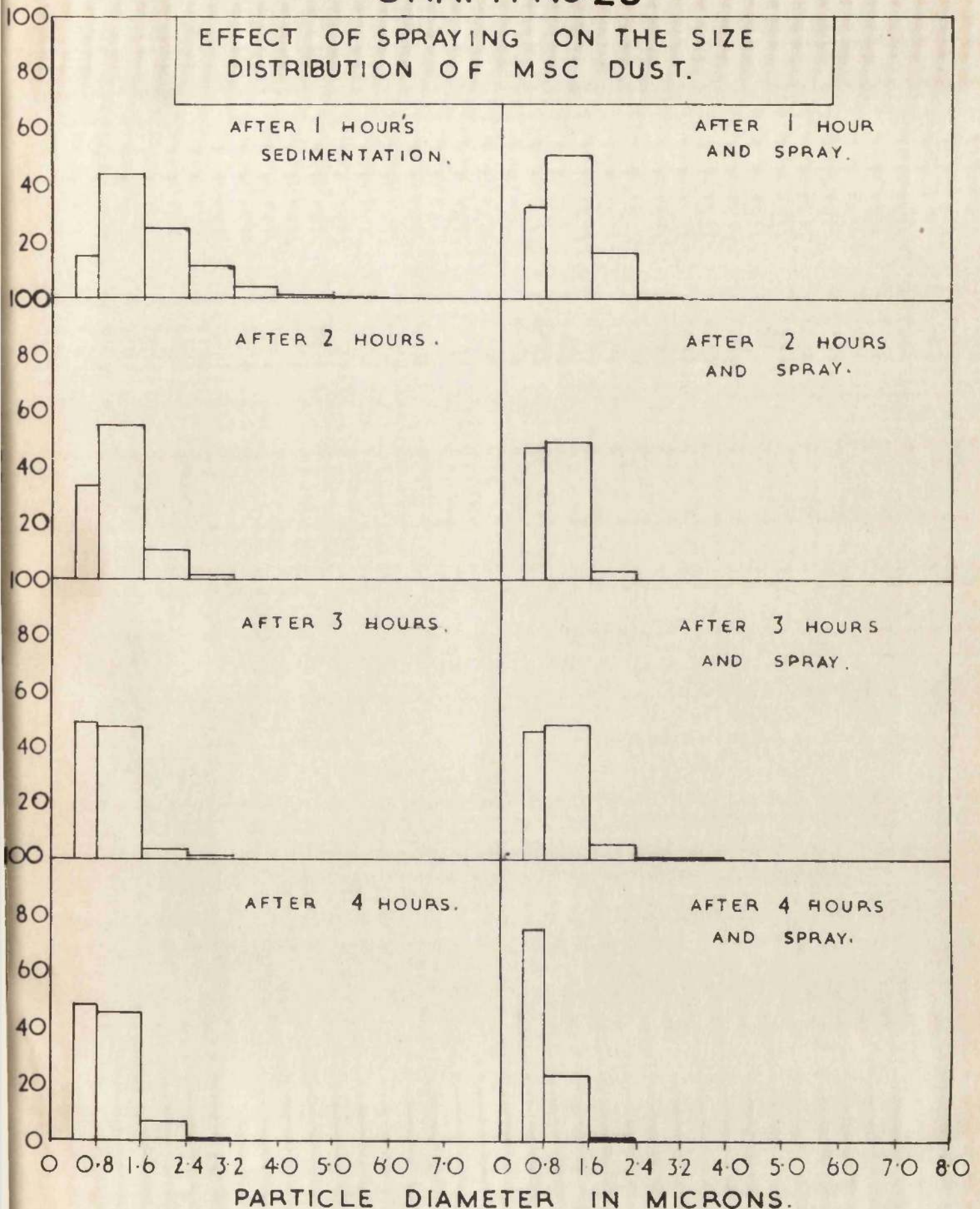
Table No. 27

Effect of Spraying on Size Distribution.

[illegible]

GRAPH No. 28

EFFECT OF SPRAYING ON THE SIZE DISTRIBUTION OF MSC DUST.



airborne dust particles varies with the size of the particle. This has been shown experimentally by Sell(74) and Vasseur(70) and by many authorities working under actual mining conditions(45). The theoretical explanation for this has been given by Davies(69) and is summarised below as it also relates efficiency of removal to size of droplet and velocity of contact, variables in the sprays which have been investigated in this work.

The efficiency of collection of particles by droplets is shown by Davies to be a

$$F(P, Re, a/R)$$

where P is the particle parameter which characterises the path of a particle starting at a certain point, Re is the Reynolds number, a/R is the ratio of particle radius to droplet radius.

The important factors in the collection of a dust particle by a water droplet are therefore seen to be:-

- (1) velocity of droplet relative to particle;
- (2) radius of particle;
- (3) radius of droplet.

In his estimate of impingement efficiency for spheres Davies(69) was guided by Vasseur's (70) results at Reynolds numbers exceeding 100 and by curves extrapolated from the data for the impingement of particles on cylinders at lower values.

In this way curves of Graph 25 were constructed showing the proportion of particles (E per cent) collected by a drop falling vertically under gravity out of all of these lying in its path. It was clear from these curves that the optimum droplet was between

0.5mm and 1mm. Small droplets were less effective because they fell so slowly that they did not collide with the dust particles but pushed them sideways in passing. The lower efficiency of large droplets was explained as follows.

The particle parameter, P , is inversely proportional to the droplet diameter so that particles of a given size have a smaller value of P relative to the larger droplets. Impingement is less efficient for smaller P . This effect outweighs the increase in terminal velocity, which is very slight for droplets greater than 4mm in diameter, so that impingement upon large droplets decreases as droplet size increases.

The curves show that a substantial gain in gravity scrubbers can be achieved by using spray droplets of the right size. Even so, suppression of dust particles below 5 microns is very poor and gravitational scrubbers are of little use for fine dusts.

Improvement in this direction can be achieved only by increasing the relative velocity between dust particle and spray droplet. This has actually been done by Kleinschmidt & Anthony(76), who placed radially-directed sprays on the axis of a cyclone; but the advantages obtained by employing droplets of the optimum size were not appreciated by the designers, nor any data given for particle size efficiency.

When deciding upon the most efficient spray to use in the suppression of a fine dust cloud, the conditions under which the spray is going to be used has to be considered. Thus, for maximum removal of dust with a fixed quantity of water, high velocity and small droplet size should be used, i.e. best atomisation. This

applies in a space where the droplets maintain their velocity and do not evaporate. When, however, a large volume is being swept, and the droplets attain their terminal velocity, a maximum efficiency of dust removal may be achieved by using a larger droplet size.

Claims are made by some investigators that particles under a certain size, 2 microns are not affected by water droplets in the spray (45). There is no apparent reason why such a limit should apply; an increase in velocity of the spray droplet and hence an increase in the Reynolds number should result in contact between the droplet and the particle.

One might offer the following explanation for the apparent inability of sprays to remove < 2 micron particles. Some of the aggregates present in the dust cloud will be broken up by the spray droplets, in many cases producing a number of smaller particles and masking the removal of the smaller particles by the spray.

It becomes obvious from this work that to report the effect of a spray on the dust conditions, and hence on the health hazard, it is essential to consider the size distribution and the number concentration of the airborne dust.

At this point it is interesting to compare the characteristics of a dust cloud which has been left to sediment for four hours with a dust cloud which has been subjected to four periods of spraying for 2 minutes at the end of 1, 2, 3, and 4 hours after charging.

The results for the concentration of the dust clouds and the size distribution of the particles in the cloud for the sedimentation test and the spraying test are shown in Table 28 and Table 29

Table No. 28.

Sedimentation Run									
Time	Conc. p.p.t.c.	Size in Microns							Total
		0.4-0.8	0.8-1.6	1.6-2.4	2.4-3.2	3.2-4.0	4.0-5.0	5.0-6.0	
1h	17,050	24.5	37.5	18.5	10.0	4.0	3.75	1.75	100
4hs	4.000	23.3	43.0	18.8	8.2	3.4	1.8	0.3	100

Table No. 29.

Spraying Run Nozzle No. 1 Water Pressure 62 lb/in. ²									
Time	Conc. p.p.t.c.	Size in Microns							Total
		0.4-0.8	0.8-1.6	1.6-2.4	2.4-3.2	3.2-4.0	4.0-5.0	5.0-6.0	
Before Spray 1h	17,050	14.9	43.9	24.8	11.2	3.9	1.0	0.3	100
After Spray 4hs	557	75.3	23.5	1.2	-	-	-	-	100

respectively.

The number of particles between 0.4 and 0.8 micron in suspension in the chamber are therefore:-

Sedimentation Test.

After 4 hours

980 p.p.c.c.

Spraying Test.

After 4 hours

420 p.p.c.c.

Although the total decrease in concentration of the dust cloud when spraying is carried out is seen to be very effective, from 4,000 to 557 p.p.c.c., the reduction in the 0.4 - 0.8 micron range of particle size is not nearly so good, from 980 p.p.c.c. to 420 p.p.c.c.

Effect of Duration of Spraying on Size Distribution.

To illustrate further the change in size distribution of the dust cloud with spraying, size distribution counts were carried out on the samples obtained for the investigation of the effect of duration of spraying on the amount of dust suppressed.

The results obtained are shown in Table 30 and also in Graph 29.

Micrographs taken of the dust on the Vicker projection microscope (Plates 3 to 9) clearly show the decrease in average particle size as the duration of spraying increases.

The samples shown on the micrographs are not truly representative of the dust cloud since the size of the particles vary across the T.P. strip and the area shown on the plates is only a section of the whole strip. The sections photographed were selected to give as accurate a picture as possible of the size range of the particles present.

It is interesting to compare the size distribution of the dust

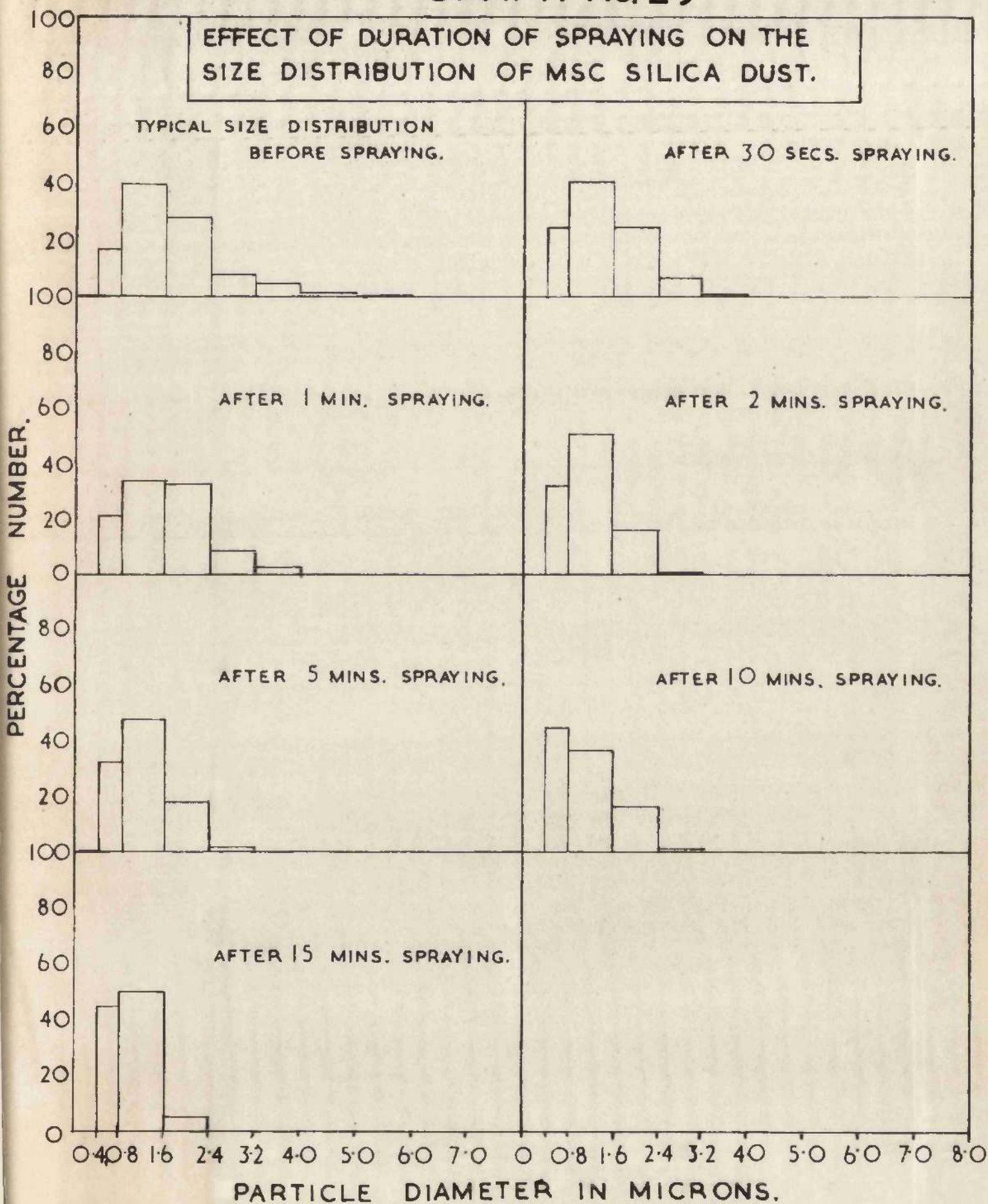
Table No. 50

Effect of Duration of Surveying on Size Distribution

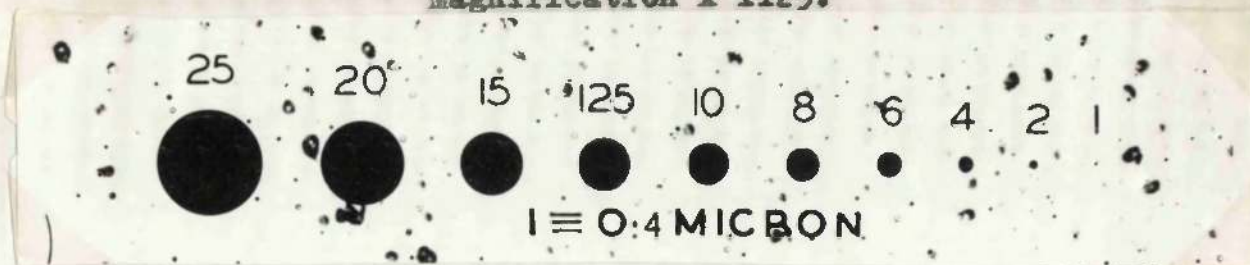
[illegible]

GRAPH No. 29

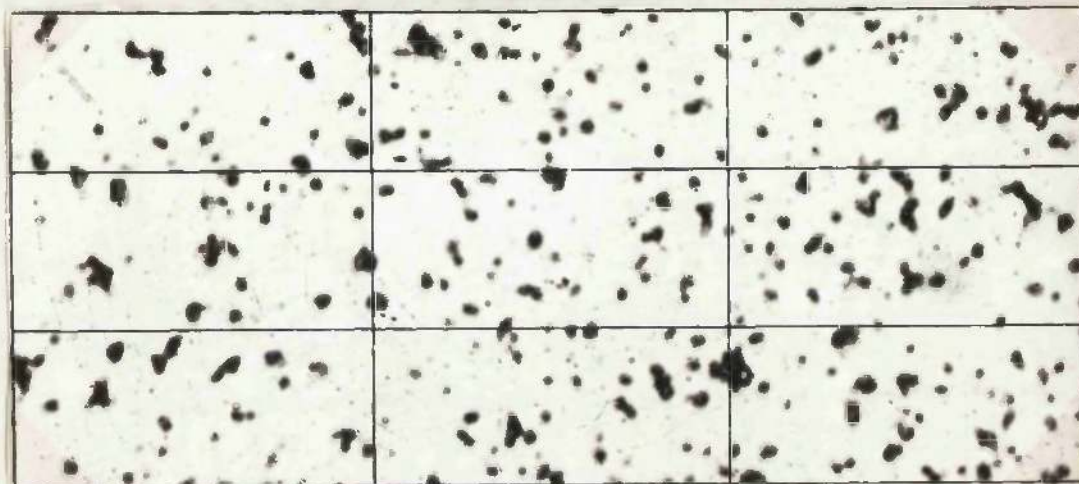
EFFECT OF DURATION OF SPRAYING ON THE
SIZE DISTRIBUTION OF MSC SILICA DUST.



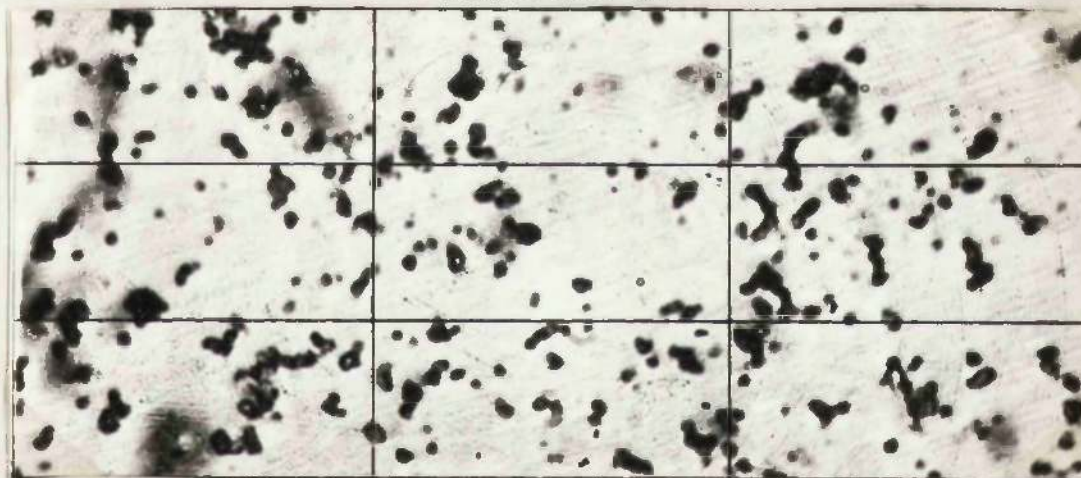
Effect of Spray on MSC Dust.
Magnification x 1125.



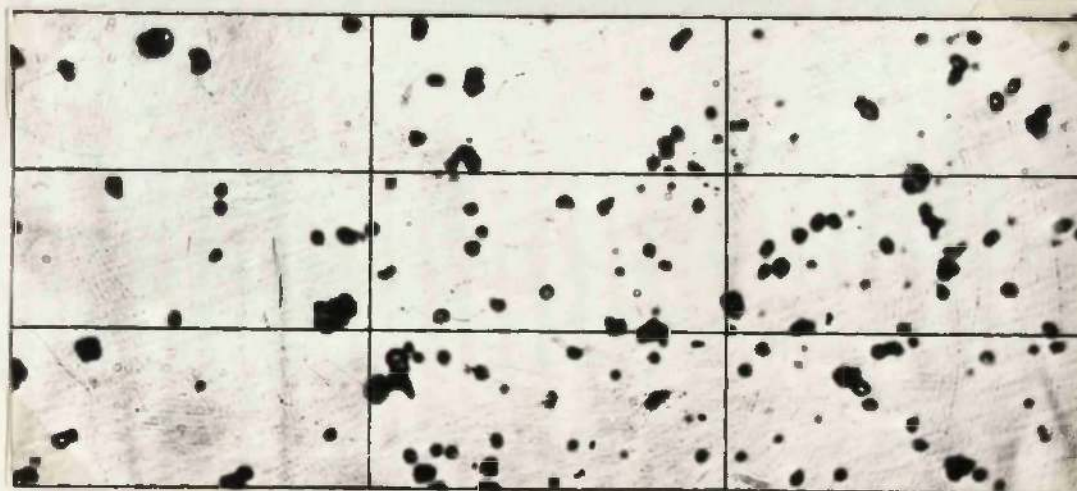
MSC Dust Immediately on Formation
Plate No. 2.



MSC Dust after Sedimenting for 1 Hour.
Plate No. 3.

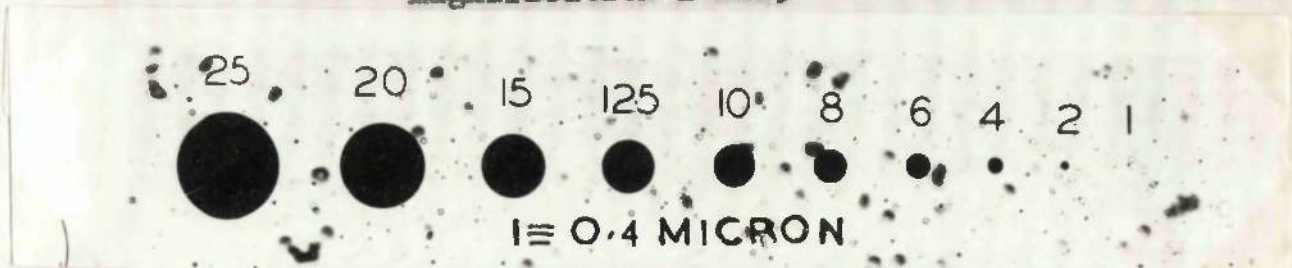


MSC Dust after Spraying for 30 Seconds.
Plate No. 4.



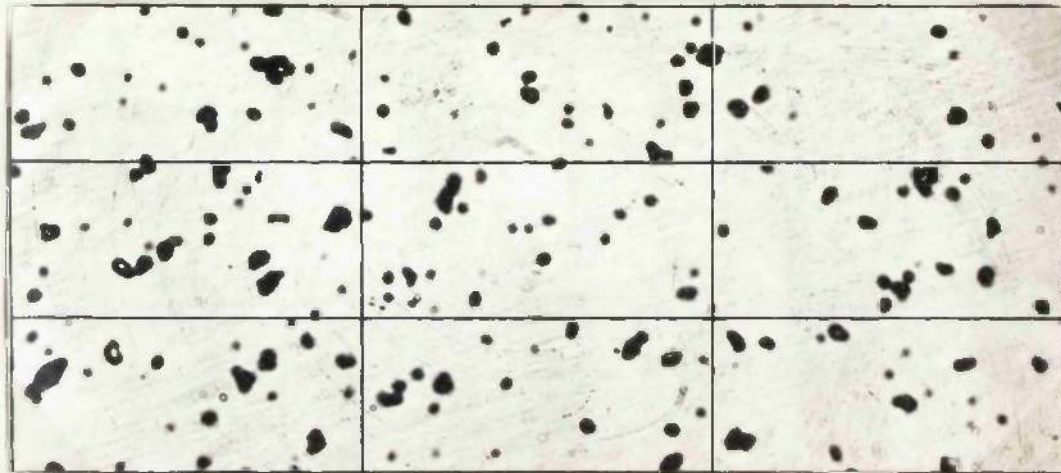
Effect of Spray on MSC Dust Contd.

Magnification x 1125



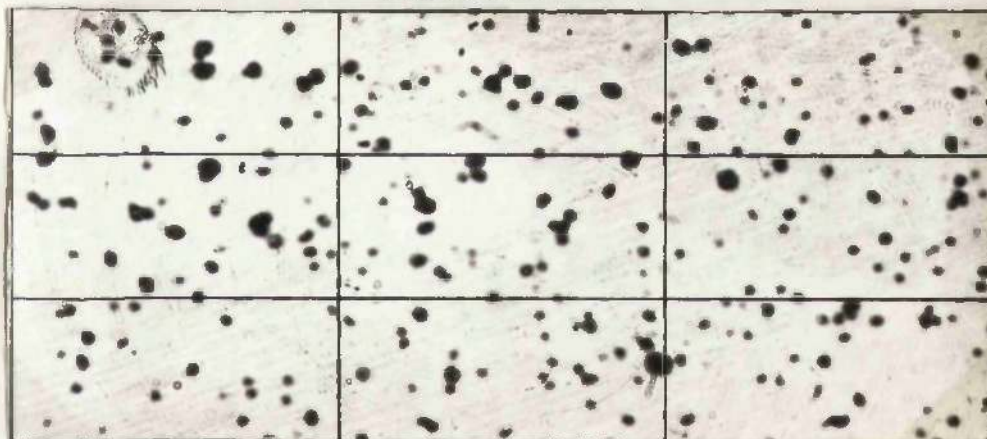
MSC Dust after Spraying for 1 Minute.

Plate No. 5.



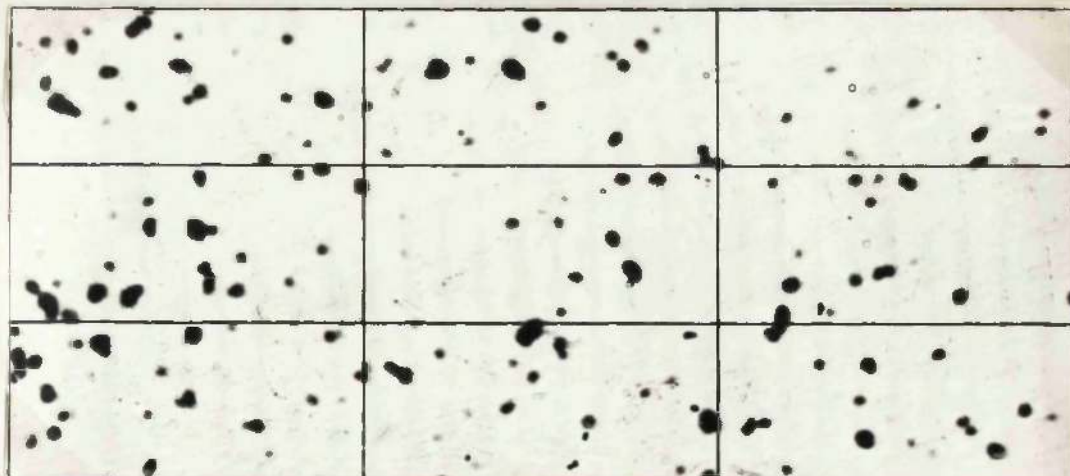
MSC Dust after Spraying for 2 Minutes.

Plate No. 6.

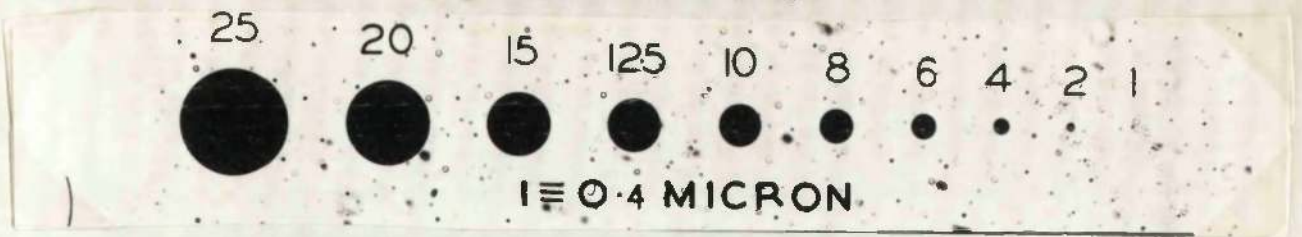


MSC Dust after Spraying for 5 Minutes.

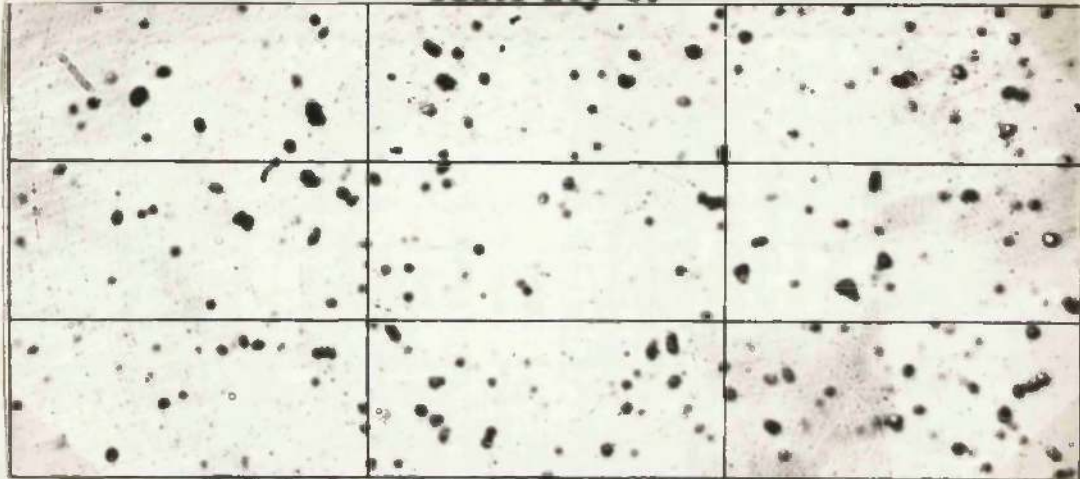
Plate No. 7.



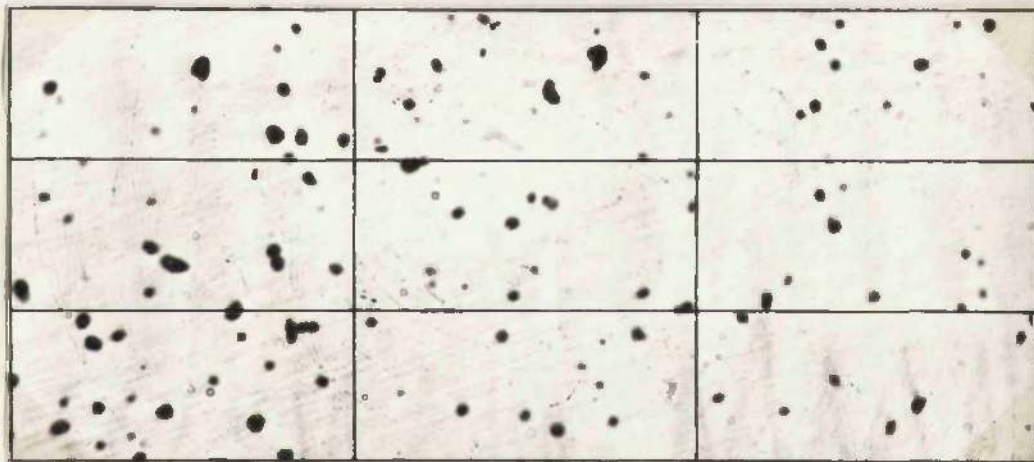
Effect of Spray on MSC Dust Contd.
Magnification x 1125.



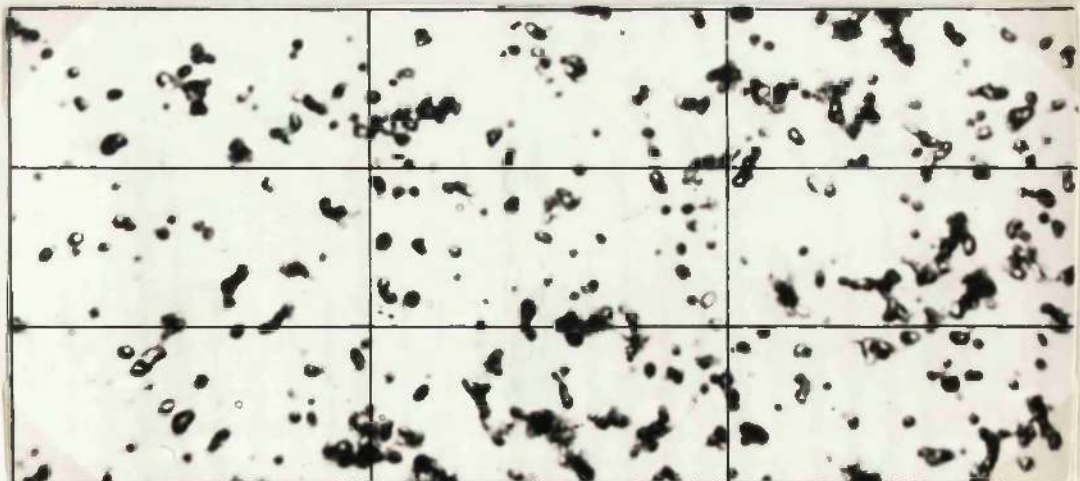
MSC Dust after Spraying for 10 Minutes
Plate No. 8.



MSC Dust after Spraying for 15 Minutes
Plate No. 9.



LAS Dust after Sedimenting for 1 Hour.
Plate No. 10.



clouds before the sprays are added to see how reproducible they are. After the periods of spraying the size distribution histograms move towards the origin; the longer the spraying period the more pronounced the move towards the origin, until after spraying for 15 minutes 95% of the dust left in suspension is less than 2 microns.

Effect of Sodium Chloride Sprays on Aggregation.

Dautrebande et al. showed the effect of a sodium chloride aerosol on a suspension of fine silica particles. The fine sodium chloride crystals were shown by electron micrographs to act as the nucleus for the formation of large silica aggregates(77,78).

The sodium chloride aerosol was formed by atomising a solution of sodium chloride and spraying the mist into a cabinet containing a cloud of silica dust. The degree of atomisation used by Dautrebande in the formation of the aerosol was much greater than that used in this work. It was decided however to show whether any aggregation resulted when a sodium chloride solution was sprayed through one of the present nozzles into a dust cloud in the chamber.

Two concentrations of sodium chloride were used, 1% and 5%, and the results compared with values obtained for the size distribution when water alone was used.

The results obtained are shown in Table 31. The results show that very little change in aggregation occurs when a 1% solution of sodium chloride is used to form a spray with No.1 nozzle.

Table No.31

Effect of Sodium Chloride Solution on Aggregation.Nozzle No.1, Water Pressure = 62 lb./in.² 1% Sodium Chloride

Size Microns	After 1h	After 1h and Spray	After 3hs	After 5hs	After 7hs	After 9hs	After 11hs
	%	%	%	%	%	%	%
0.4-0.8	17.9	30.9	28.3	19.3	22.2	4.0	18.4
0.8-1.6	43.8	53.5	51.4	55.2	53.7	34.4	62.0
1.6-2.4	23.6	13.2	14.0	20.0	20.2	27.7	16.9
2.4-3.2	9.0	1.9	5.2	4.9	2.9	4.5	2.7
3.2-4.0	4.4	0.5	1.1	0.8	1.0	0.5	
4.0-5.0	0.65						
5.0-6.0	0.65						
	100	100	100	100	100	100	100

Nozzle No.1, Water Pressure = 62 lb./in.² 5% Sodium Chloride

Size Microns	After 1h	After 1h and Spray	After 3hs	After 5hs	After 7hs	After 9hs	
	%	%	%	%	%	%	
0.4-0.8	19.1	25.8	19.5	26.6	11.3	20.7	
0.8-1.6	44.7	44.7	42.6	38.8	43.5	37.6	
1.6-2.4	20.1	23.5	23.4	27.0	32.9	31.9	
2.4-3.2	13.0	5.3	7.4	6.6	10.0	7.8	
3.2-4.0	2.7	0.9	1.6	1.0	1.9	2.0	
4.0-5.0	0.4		0.5		0.4		
5.0-6.0							
	100	100	100	100	100	100	

When a 5% solution of sodium chloride is used to form a spray under the same conditions a difference in the amount of dust which aggregates becomes evident immediately after the spraying period and lasts up to 9 hours. The use of a 5% solution would therefore be expected to be more effective in the suppression of fine silica dust since aggregates would be formed which could be more easily knocked down owing to their greater inertia. Against this increase in aggregation one has to balance a slight increase in surface tension of the spray solution which would result in a very slight decrease in atomisation. The presence of ionisable compounds in the spray solution have been shown to destroy the electrical charges which otherwise would exist on the droplets (75). This change would be expected to affect the efficiency of the spray in some way.

The Influence of a Radioactive Static Eliminator (R.A.S.E.) on Aggregation.

Since some authorities consider the aggregation of fine particles to be affected by their electrical properties (77,78) it was decided to try to show whether it was possible to alter the electrical character of the particles. By this means it was hoped that a difference in aggregation would be detected.

It is well established(79,80,81) that fine particles of silica dust have an electric charge when blown into suspension in the air in a manner similar to that used in this work. There is some doubt as to the nature of the electric charge. Some authorities claim the dust cloud to be overall neutral, being made up of positively charged and negatively charged particles in exactly the same proportion, with some neutral particles(62). Others claim that the chemical character-

istics of the compound determine the nature of the charge on the particles and showed silica dust to have a positive charge which is ascribed to its acidic character(83).

It seems a reasonable assumption that the electrical charges on such particles will influence their aggregation. This opinion is shared by Gibb(80).

In order to affect the electrical character of the dust cloud the cloud was exposed to a R.A.S.E. unit, which is a source of β -rays. The isotope used in the unit is thallium 204 which has a half life of 217 years emitting β -rays having a maximum energy of 0.775 MeV. This is regarded as a comparatively weak unit and has a maximum range in terms of mass, 0.28g/sq.cm which gives a range of 230 cms for air.

Procedure for Determining the Effect of the Unit.

The R.A.S.E. unit (82), with the protective cover removed, was suspended in the chamber before this was charged with dust. The chamber was charged in the normal manner with MSC dust and a sample of the dust cloud withdrawn by the T.P., immediately on formation of the cloud, after $\frac{1}{2}$ hour, 1, 3, 5 and $9\frac{1}{2}$ hours. The size distribution does not alter appreciably over this period.

Comparison of the size distribution over this period with the distribution over 9 hours when no R.A.S.E. unit was used shows the results to agree very closely, except for the sample withdrawn immediately the cloud was formed(Tables 32 and 33).

It would appear then that the effect of the R.A.S.E. unit is

Table No.32.

Effect of Radio Active Static Eliminator on Aggregation,

No R.A.S.E. Unit

Size Microns	Immediately	After 30mins	After 1h	After 3hs	After 6hs	After 12hs
0.4-0.8	28.1		24.5	23.3	13.0	10.4
0.8-1.6	47.8		37.5	41.6	39.0	47.4
1.6-2.4	20.9		18.5	19.0	27.4	23.3
2.4-3.2	3.2		10.1	9.5	11.4	9.6
3.2-4.0			4.0	2.9	5.4	5.7
4.0-5.0			3.75	2.0	3.25	1.9
5.0-6.0			1.75	1.7	0.55	1.7
6.0-8.0						
	100		100	100	100	100

Using R.A.S.E. Unit

Size Microns	Immediately	After 30mins	After 1h	After 3hs	After 6hs	After 12hs
0.4-0.8	23.1	22.5	20.2	14.6	17.25	19.2
0.8-1.6	32.3	31.4	34.4	32.6	33.0	29.4
1.6-2.4	24.3	22.0	26.4	29.8	26.5	29.7
2.4-3.2	11.9	13.6	11.0	12.6	14.0	13.3
3.2-4.0	6.4	7.8	5.9	7.2	5.25	6.4
4.0-5.0	1.4	1.9	1.6	2.3	3.25	1.5
5.0-6.0	0.6	0.8	0.5	0.6	0.75	0.25
6.0-8.0				0.3		0.25
	100	100	100	100	100	100

Table No. 33

Effect of Radioactive Station Indicator on Aggregation.

[illegible]

instantaneous. This suggests that the particles are predominantly charged one way and are being kept apart by their mutual repulsion like the particles in a colloidal solution. The ions produced by the unit will then be absorbed by the charged silica particles and the fine particles will be able to aggregate. This effect will be present in the chamber under normal conditions, owing to the presence of gaseous ions in the atmosphere, but to a much lesser degree. The fact that the final state of aggregation is the same with and without the R.A.S.E. unit suggests that the mechanism is the same in both cases but that it is accelerated by the use of the unit.

An alternative explanation is that the particles are initially neutral but pick up charges of both signs by collision with the ions produced by the R.A.S.E. unit, and then attract each other. The former explanation is preferred.

Conclusions.

The size distribution of a dust cloud was shown to alter during the first hour in suspension in the chamber but no change was detected in the size distribution during the next eleven hours. After nineteen hours the sedimentation of the larger particles gave a dust cloud with a size distribution approximately equal to the original.

The effect of spraying was to remove or break up the larger particles and aggregates giving, as a result, a dust cloud with a higher percentage of harmful dust particles.

The effect of a 5% sodium chloride solution was to give a slight increase in the aggregation of the dust particles. This effect was not detected when a 1% sodium chloride solution was used.

The use of a Radioactive Static Eliminator resulted in the immediate aggregation of a dust cloud to a size distribution comparable with a period of sedimenting for one hour. No further change in the size distribution was detected over the next 8½ hours.

General Discussion and Suggestions for Future Work.

The Estimation of Dust Concentration.

Exploratory work on the effect of aqueous sprays on the suppression of airborne dust had been carried out by Massie (41) using the light extinction method to estimate the concentration. The same method was employed in the initial stages of the present work, but since the results obtained were difficult to interpret with respect to health hazard and were subject to a number of errors, (e.g. the fatigue of the photoelectric cells and the effect of particle size on the amount of light obscured) subsequent experiments were carried out using the T.P. The T.P. had the advantage that it could be used to estimate the dust over a wide range of concentration and also enable the size distribution of the cloud to be estimated.

In further investigations on the settling characteristics of airborne dusts and the effect of sprays on the dust it would be advisable to connect the P.E.C. systems to a multi-point automatic recorder. This would allow the operator to obtain results on the behaviour of the dust cloud with respect to surface area and also to use the T.P. to obtain the size distribution of the cloud. To operate the recorder it would be necessary to use valve-type photo-cells, such as those produced by Radio Electronics Ltd., Merton Road, London.

The Suppression of Airborne Dust.

The experiments have shown that a fine silica dust cloud is affected by an aqueous spray. The most effective suppression is achieved at high atomisation of the spray solution. This can be

achieved by increasing the water pressure or lowering the surface tension at low water pressure. The efficiency of a spray solution in suppressing a dust has been shown to be lowered if the vapour pressure of the solution is increased.

It should be borne in mind when considering the efficiency of a spray in reducing the dust concentration that the spray will be more efficient in the chamber than under ordinary working conditions. The reason for this is the confined space and the turbulence in the chamber, which will increase the likelihood of contact between droplet and particle. The rate of evaporation of the water droplets will not be so great in the dust chamber after the initial spraying period, owing to the high relative humidity which will then exist. This factor will also contribute to a higher dust-suppression efficiency than would be found under mining conditions.

The effect of sprays on different dusts should be investigated, e.g. dusts soluble in water, to show whether the interfacial tension of the droplet and the particle plays any part in the knockdown of the dusts. It is not considered by the writer to have an effect on the efficiency of suppression, since alteration of the surface tension of the water droplets (and, therefore, of the interfacial tension of the particles and the droplets) was shown to be ineffective provided that the atomisation remained unaltered.

The Effect of the R.A.S.E. unit.

Investigation of the effect of influencing the electrostatic charge on the fine silica particles is considered by the writer to

be the most promising line of research to follow. R.A.S.E. units of greater strength should be used and their effect on the rate of aggregation followed. It is questionable whether such a method of accelerating aggregation could be applied in industry without causing ill effects to the health of the workers, but it would be an investigation of fundamental importance.

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